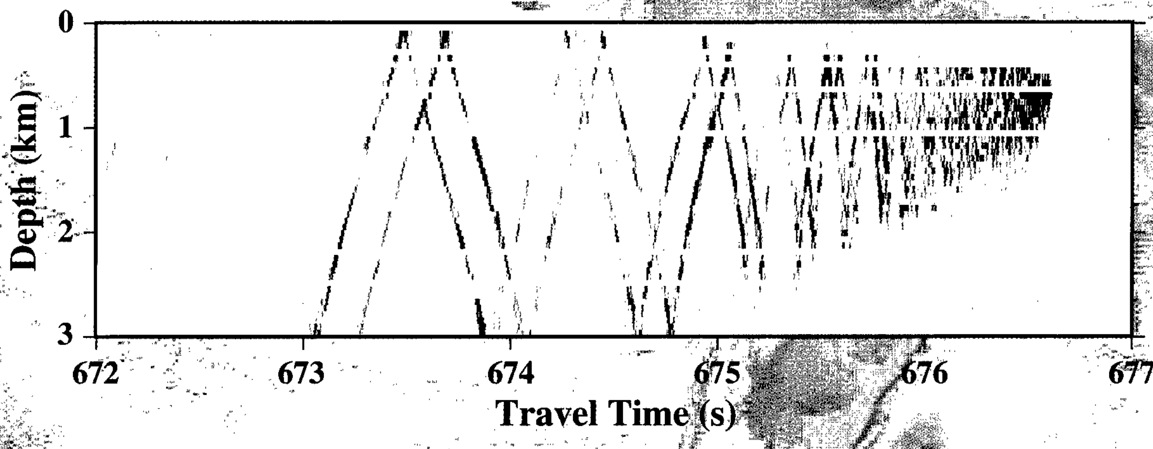
Report on the Office of Naval Research Long-Range Propagation Workshop

3–4 March 1997

by

Peter F. Worcester



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ONR Long-Range Acoustic Propagation Workshop
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Abstract for final report.

The Office of Naval Research, Code 321 OA, sponsored a workshop on long-range acoustic propagation in the ocean on March 3–4, 1997. The goals of the workshop were to clarify the fundamental outstanding scientific issues in the propagation and scattering of sound transmitted over several hundred to several thousand kilometers in the ocean and to identify research opportunities to improve our understanding of long-range propagation. The workshop was also designed (i) to promote communication and integration among the basic research investigators and between the 6.1 and 6.2 communities on long-range acoustic propagation in the ocean, (ii) to suggest where field experiments are needed, and (iii) to identify potential Navy applicability. This report summarizes the recommendations emerging from the Workshop.

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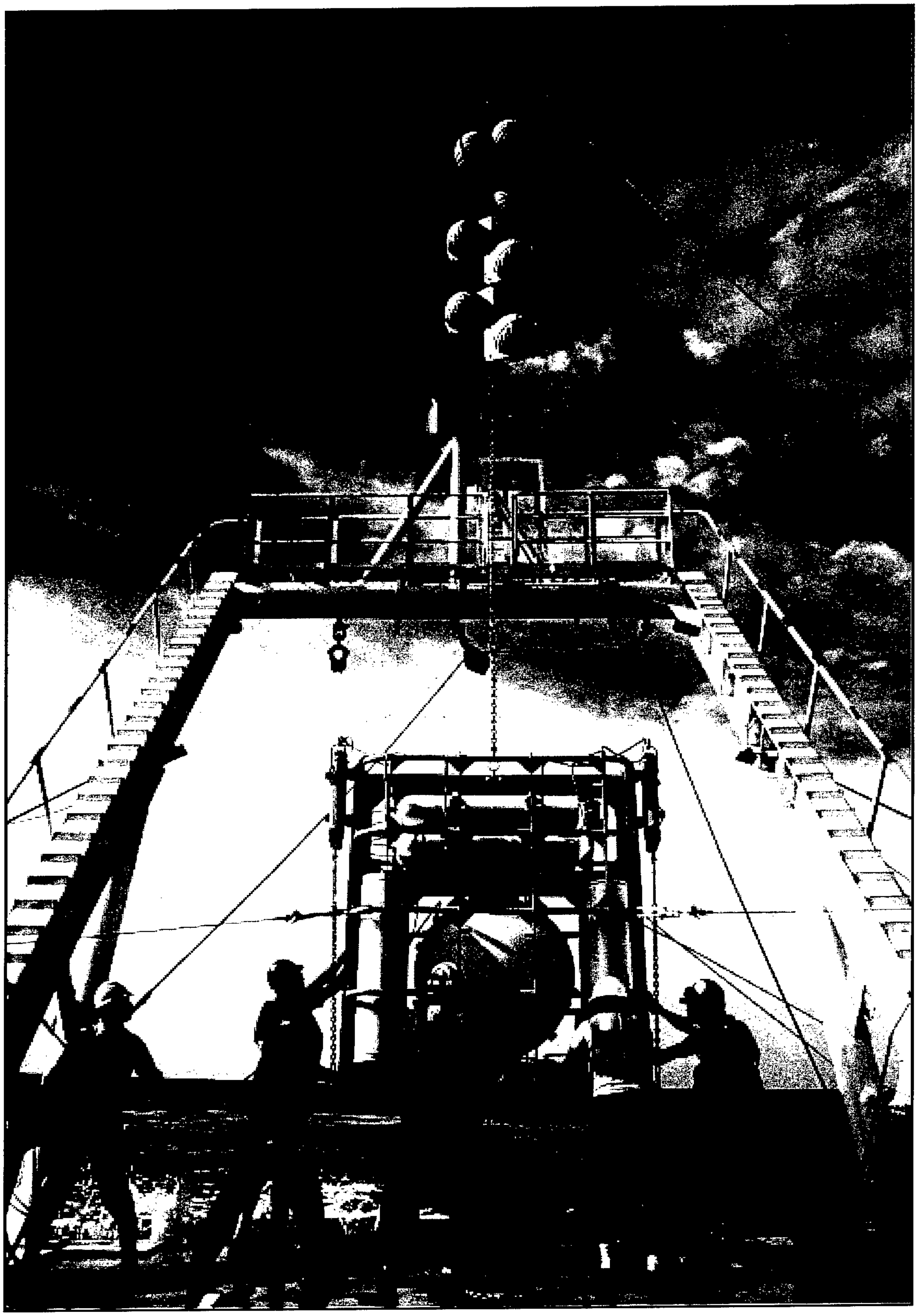
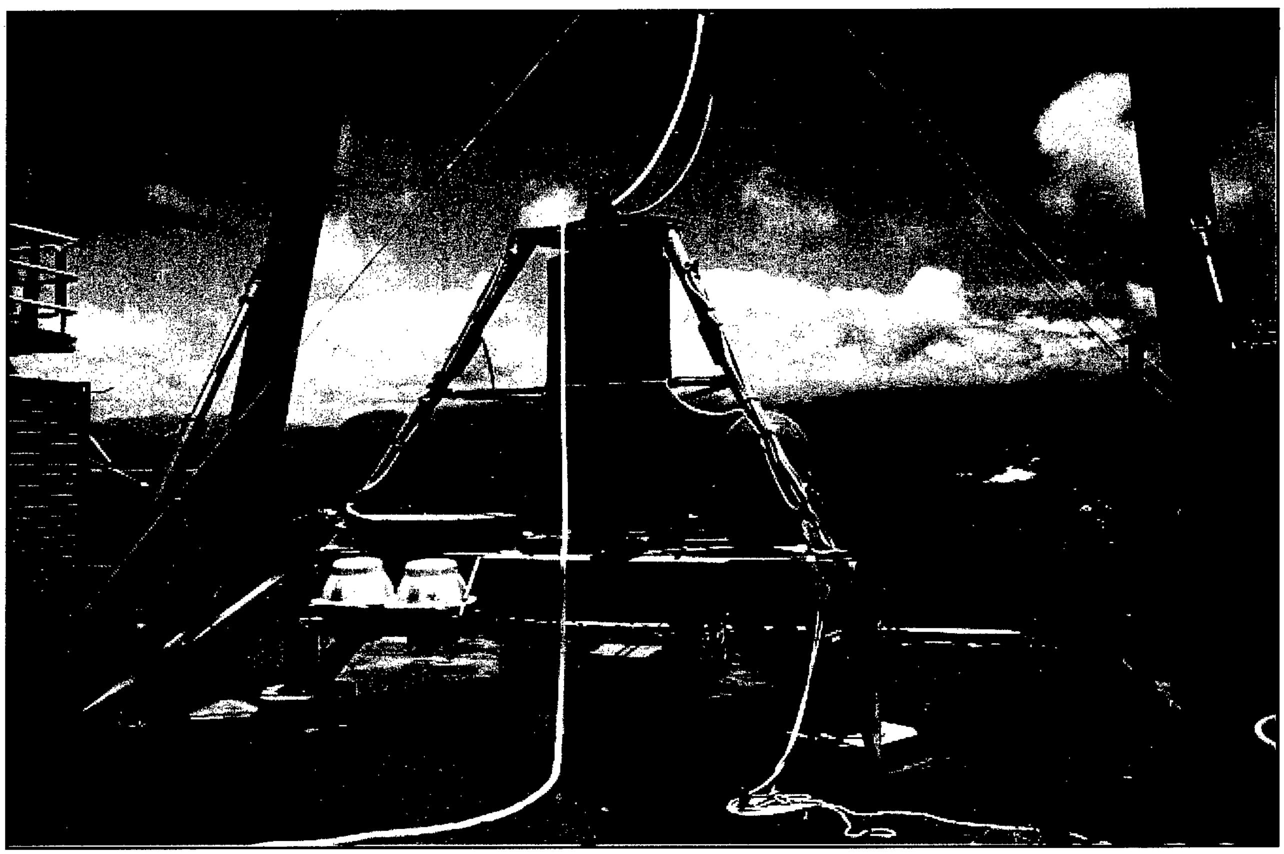


Above: Deployment of an HLF-5 acoustic source (250 Hz) from the OCP *Seacon* near Bermuda during July, 1990 for the Applied Tomography Experiment.

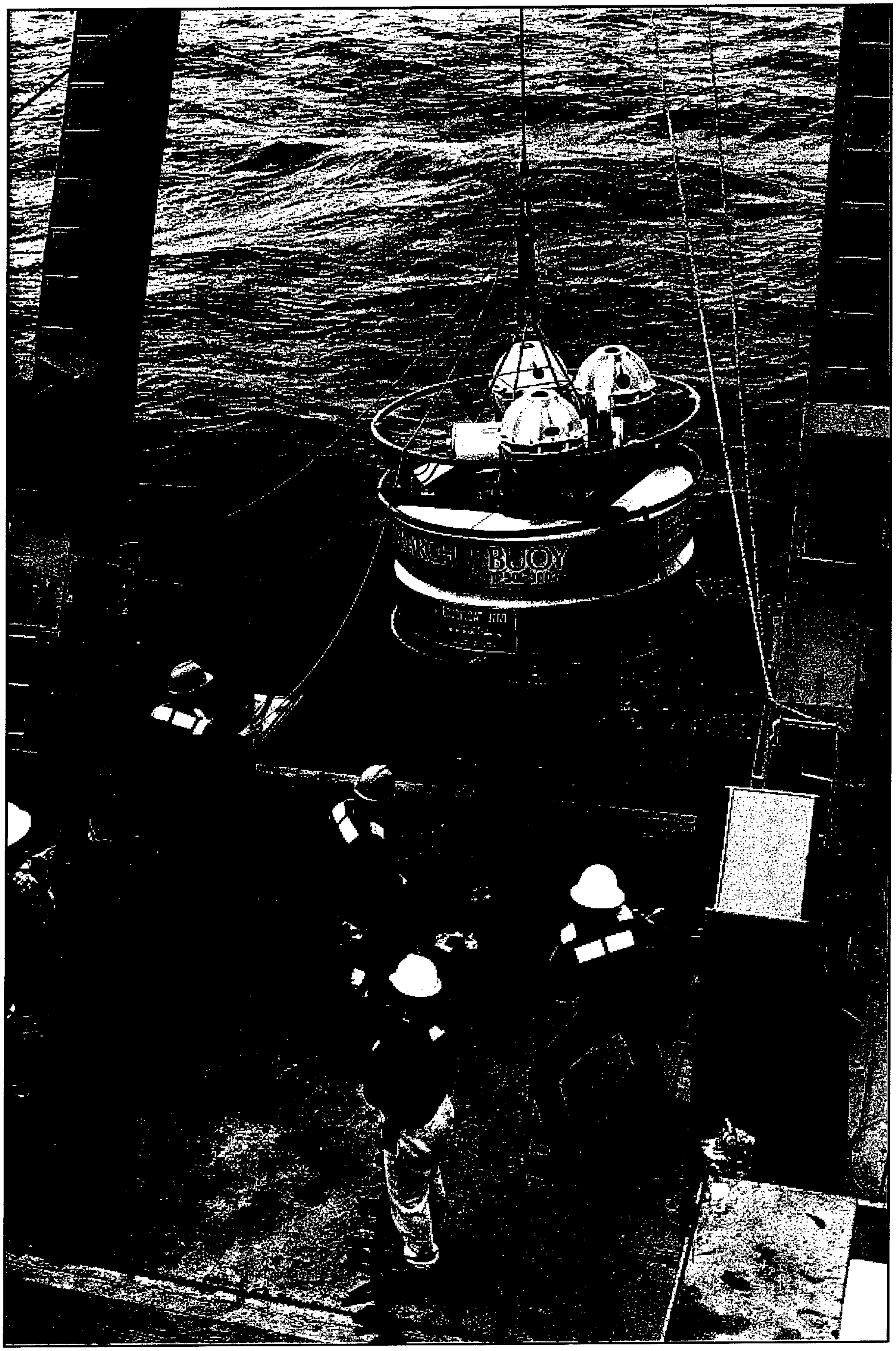
Cover: Broadband acoustic signal transmitted from an HLF-5 acoustic source (250 Hz), **S**, to a 3-km long vertical receiving array 1,000-km distant, **R**, during the SLICE89 experiment in July, 1989. Transmission paths from the ATOC Pioneer Seamount source (75 Hz) are also shown.

ACKNOWLEDGMENTS

The Long-Range Propagation Workshop upon which this report is based was organized at the instigation of and with support from Dr. Jeffrey Simmen of the Office of Naval Research. I am grateful to the two discussion group leaders, Dr. Robert Spindel and Dr. Michael Brown, for keeping the discussions collegial and productive and for their help in the preparation of this report. I am also grateful to Michael Brown, John Colosi, Bruce Cornuelle, Brian Dushaw, Matthew Dzieciuch, Jeffrey Simmen, and Robert Spindel for critically reviewing this report. Mrs. Bev Kuhn of the Office of Naval Research and Ms. Lisa Day of the Scripps Institution of Oceanography played essential roles in the planning and execution of the Workshop. The comfortable facilities and friendly staff of the Lake Arrowhead Conference Center of the University of California helped promote useful interactions between the Workshop participants. Financial support for the planning of the Workshop and the preparation of this report was provided by ONR Grant N00014-97-1-0269.



ATOC HX-554 acoustic source (75 Hz) on the DSVSS *Laney Chouest* ready for deployment off Kauai during July, 1997.



Subsurface float deployment from the R/V *Melville* during July, 1998 for the North Pacific Acoustic Laboratory (NPAL) experiment. The subsurface float can carry up to four pop-up buoys for mid-experiment data retrieval.

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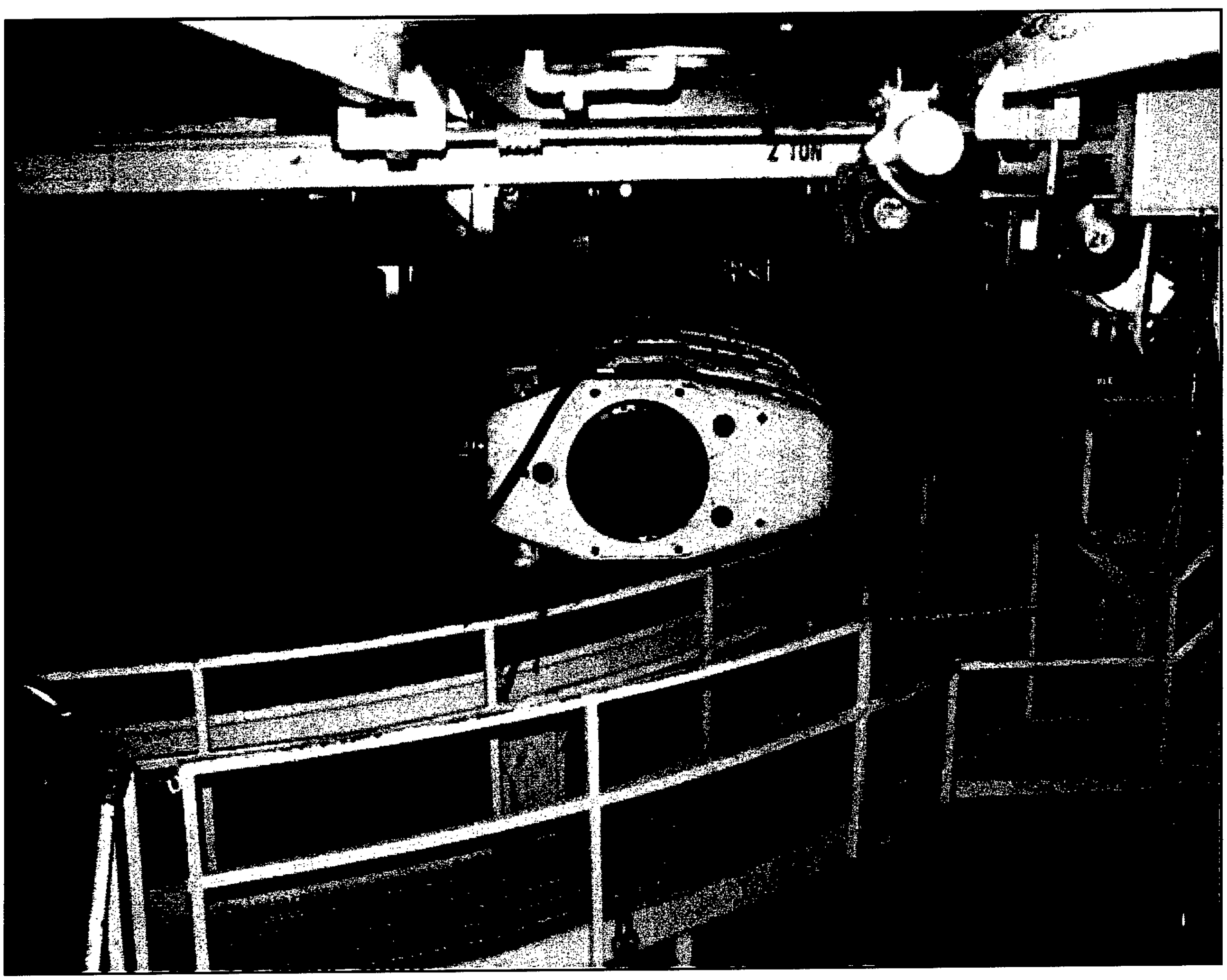
ABSTRACT

The Office of Naval Research, Code 321 OA, sponsored a workshop on long-range acoustic propagation in the ocean on March 3–4, 1997. The goals of the workshop were to clarify the fundamental outstanding scientific issues in the propagation and scattering of sound transmitted over several hundred to several thousand kilometers in the ocean and to identify research opportunities to improve our understanding of long-range propagation. The workshop was also designed (i) to promote communication and integration among the basic research investigators and between the 6.1 and 6.2 communities on long-range acoustic propagation in the ocean, (ii) to suggest where field experiments are needed, and (iii) to identify potential Navy applicability. This report summarizes the recommendations emerging from the Workshop.



HLF-4LL acoustic sources (57 Hz) aboard the R/V *Cory Chouest* during the Heard Island Feasibility Test in January, 1991.

EXECUTIVE SUMMARY

The Ocean Acoustics Program of the Office of Naval Research, Code 321 OA, sponsored a workshop on long-range acoustic propagation in the ocean on March 3–4, 1997, at the Lake Arrowhead Conference Center of the University of California. The goals of the workshop were to clarify the fundamental outstanding scientific issues in the propagation and scattering of sound transmitted over several hundred to several thousand kilometers in the ocean and to identify research opportunities to improve our understanding of long-range propagation. After an initial day of short presentations by the participants, two working groups were formed and asked to independently summarize the outstanding research issues in long-range acoustic propagation. A plenary session followed the presentation of the reports from both groups, at which the reports were compared and discussed.

It is well known that the physics governing long-range acoustic propagation in the ocean are, in almost all cases of interest, adequately described by the wave equation. The basic scientific issues that arise are due to the complex effects that can occur when acoustic signals propagate to great distances through a turbulent ocean that fluctuates on all time and space scales and when the signals interact with rough surface and bottom boundaries.

The key issues are:

Signal Coherence: Ocean processes that reduce the temporal and spatial phase coherence of signals that propagate over long ranges in the ocean impose fundamental limits on what can be achieved using advanced signal processing techniques.

The fundamental limits to phase-coherent processing at long range are not known at this time and may allow substantially greater processing gains than once thought.

Experimental measurements of the full 3-D wave front coherence (horizontal, vertical, and temporal) of resolved ray and/or modal arrivals are sorely lacking. The North Pacific Acoustic Laboratory (NPAL) experiment is a substantial effort in this direction, but is limited to a single range and frequency band. The dependence of internal-wave-induced scattering on range, acoustic frequency, and signal bandwidth has not been adequately determined experimentally.

Ambient Noise: The noise field at low frequencies can be expected to have substantial intermittent structure ("granularity") that can in principle be exploited by appropriately designed receiving systems and signal processing techniques for detection and localization purposes.

The extent to which advanced adaptive array processing methods can exploit the structure of the ambient noise field to achieve improved signal-to-noise ratios at long ranges is unknown, but may be substantial.

Experimental progress in determining the extent to which the structure of the ambient noise field can be exploited to achieve improved signal-to-noise ratios has been hampered by the difficulty of constructing adequate receiving arrays to fully characterize the spatial and temporal structure of the noise field.

Ocean Characterization: Advanced signal processing techniques such as matched field processing require that the medium through which the acoustic signals propagate be accurately characterized.

Acoustic remote sensing methods have the potential to help characterize the propagation environment for use by advanced signal processing techniques by making it feasible to rapidly and repeatedly measure the sound-speed field over large ocean volumes.

Although ocean acoustic tomography is a well-developed field, interactions between the adaptive signal processing and tomographic communities have been limited to date.

Specific research opportunities are summarized in this report under the headings Theoretical, Computer Simulations and Modeling, and Experimental, although there is considerable interaction and overlap between the various categories. Finally, we argue that a long-term Ocean Acoustic Observatory is needed.

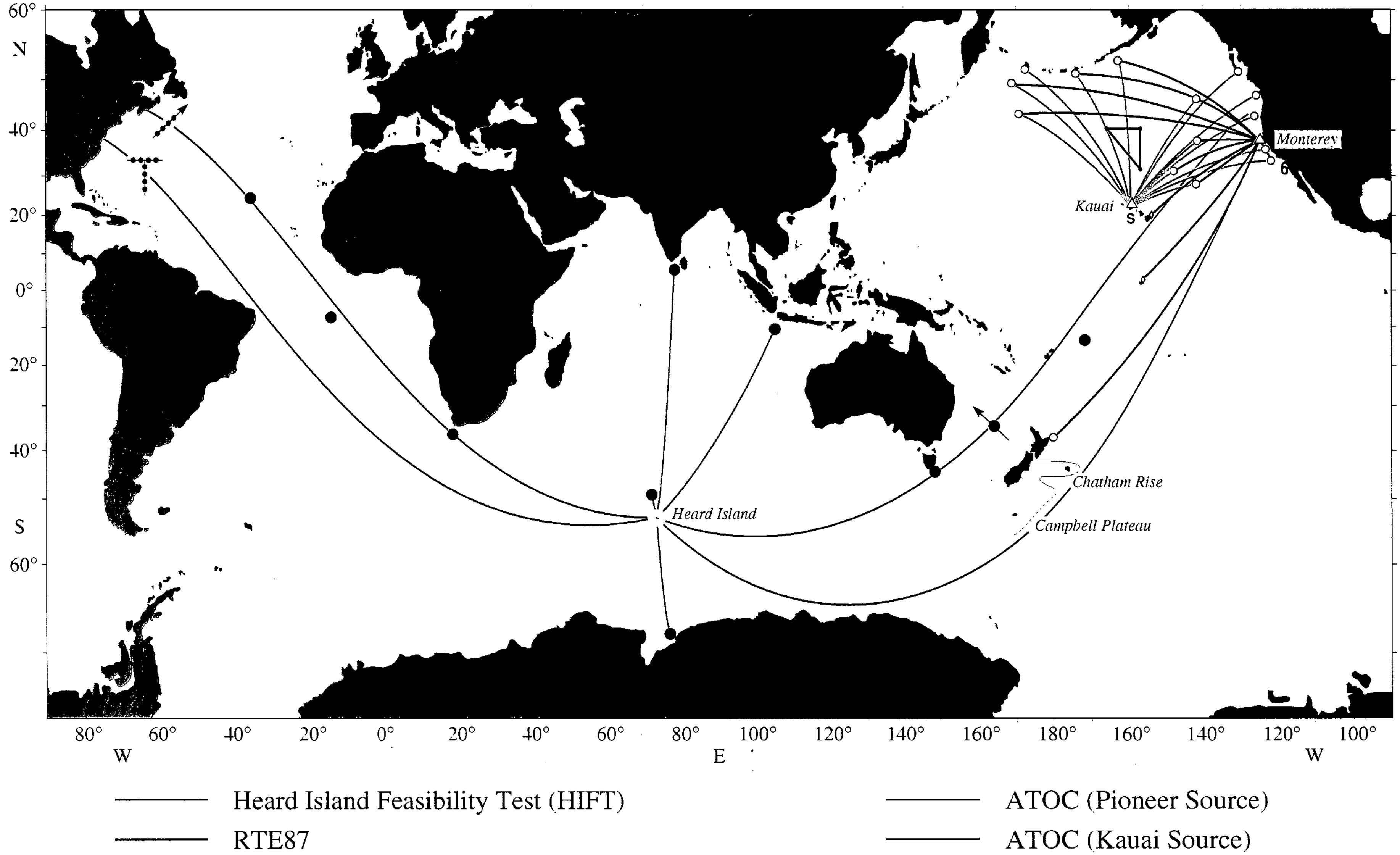
Ocean Acoustic Observatory.

The size of the receiving arrays required to measure and exploit signal coherence and the structure of the noise field are too large to be installed by a single investigator or experimental group. An Ocean Acoustic Observatory is needed to allow the requisite 3-D aperture to be assembled over time, as funding permits. A dynamic, evolving Observatory is envisioned, whose design and implementation would change as our understanding and needs evolve. The underlying enabling technology would be one or more fiber-optic cables to connect the array site to shore.

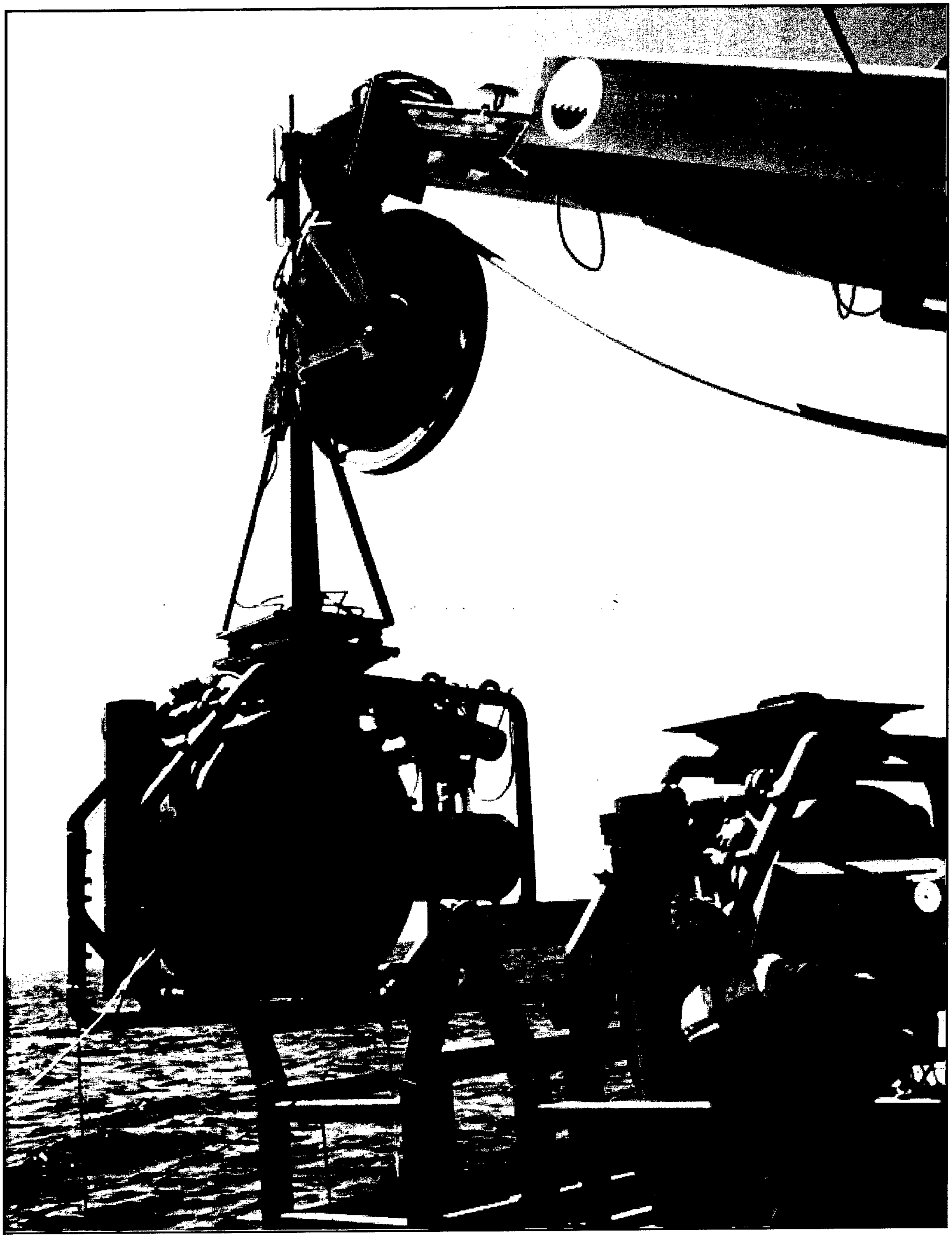
Such an Observatory would not only serve to advance our understanding of long-range propagation and the structure of the ambient noise field, but would also provide invaluable data on the geophysical and biological processes that contribute to ambient noise, including undersea earthquakes and volcanic eruptions, marine mammal vocalizations and distributions, and surface processes such as rain and wind. As one component of an active tomographic system, an Observatory would also provide data on ocean thermal and current structure.

Subsequent to the Workshop reported on here, the JASON Advisory Group studied the utility of an ocean acoustic observatory and endorsed the concept pending in depth analysis. As a result, ONR commissioned a Phase I Study of the concept which also supports the implementation of an observatory.

Americo Rivera and Bruce Howe fine tune instruments on board the R/V *Melville* for NPAL during July, 1998.



Gyre, basin, and global-scale transmission paths for the 1987 Reciprocal Tomography Experiment (RTE87), the Heard Island Feasibility Test (HIFT), and the Acoustic Thermometry of Ocean Climate (ATOC) project.



Deployment of an HLF-6A acoustic source (28 Hz and 84 Hz) near Pioneer Seamount off central California for the Dual-Frequency Test in July, 1996.

1. INTRODUCTION

The Ocean Acoustics Program of the Office of Naval Research sponsored a workshop on long-range acoustic propagation in the ocean on March 3–4, 1997. A group of 34 investigators and program managers (Appendix A) assembled at the Lake Arrowhead Conference Center of the University of California for the workshop. Investigator specialties included propagation, scattering, signal processing, ambient noise, physical oceanography, inverse methods, and geoacoustics. Both the basic research (6.1) and exploratory development (6.2) communities were represented so as to enable vertical, as well as horizontal, integration.

The goals of the workshop were to clarify the fundamental outstanding scientific issues in the propagation and scattering of sound transmitted over several hundred to several thousand kilometers in the ocean and to identify research opportunities to improve our understanding of long-range propagation. The workshop was also designed (i) to promote communication and integration among the basic research investigators and between the 6.1 and 6.2 communities on long-range acoustic propagation in the ocean, (ii) to suggest where field experiments are needed, and (iii) to identify potential Navy applicability.

This Workshop is one of three recently sponsored by the Office of Naval Research, Code 321 OA, to determine the outstanding scientific issues in underwater acoustics and to identify the associated research opportunities. The other two dealt with shallow-water acoustics (Lynch, 1997) and high-frequency acoustics (Thorsos, 1997).

Structure of Workshop

The first day of the workshop was devoted to 22 short presentations (Appendix B). Following an introduction by Dr. Jeffrey Simmen (ONR), the presentations were organized into five categories:

- Measurements
- Propagation Modeling
- Internal-Wave-Induced Scattering
- Mesoscale-Induced Scattering
- Future Field Work

Abstracts from all of the presentations are included in Appendix C.

On the second day the participants divided into two working groups, led by Dr. Robert Spindel and Dr. Michael Brown. Both working groups were charged with independently summarizing the outstanding research issues in long-range acoustic propagation. A plenary session followed the presentation of the reports from both groups, providing the opportunity for lively and informative discussions.

A Disclaimer

In developing this report, I chose to use the workshop discussions as a springboard to explore the outstanding scientific issues in and to identify opportunities to improve our understanding of long-range propagation. This report therefore does not necessarily represent a consensus of those who participated in the Workshop. My goal is to present a coherent and, I hope, useful summary.

In the sections that follow, references to results of particular investigators and to published work have been kept to a minimum. Those references included are certainly not comprehensive.

Related Reports

There have been a series of previous efforts to identify the outstanding scientific issues in underwater acoustics. The Naval Studies Board of the National Research Council convened Panels on Research Opportunities in Underwater Acoustics in 1986 and again in 1990. Their reports still provide useful background (Panel on Research Opportunities in Underwater Acoustics, Naval Studies Board, 1986; Panel on ONR Research Opportunities in Underwater Acoustics, Naval Studies Board, 1990). More recently the Naval Studies Board convened a Panel on Undersea Warfare that discussed the importance of antisubmarine warfare to future Navy missions and the science and technology issues that need to be resolved to determine the ultimate limits to the use of ocean acoustics for antisubmarine warfare (Panel on Undersea Warfare, Committee on Technology for Future Naval Forces, Naval Studies Board, 1997). Finally, the JASON committee of the Department of Defense recently completed a summer study entitled "Ultimate Limits to Passive Acoustic ASW" (Callan and Levine, Study Leaders, unpublished, 1997) in which the factors limiting passive ASW performance were surveyed and the extent to which the limits to passive underwater acoustics are known were reviewed.

2. LONG-RANGE ACOUSTIC PROPAGATION IN THE OCEAN: BACKGROUND

The ocean is transparent to sound and largely opaque to electromagnetic radiation. Remote sensing of the ocean interior—whether to measure ocean temperatures and currents, study undersea volcanoes and earthquakes, determine marine mammal distributions and behavior, or track submarines—must therefore rely on acoustic methods rather than electromagnetic methods. Similarly, the performance of more utilitarian functions—such as undersea navigation and data telemetry—must also rely on acoustic signals. It is well known that the physics governing long-range acoustic propagation in the ocean are, in almost all cases of interest, adequately described by the wave equation. The basic scientific issues that arise are due to the complex effects that can occur when acoustic signals propagate to great distances through a turbulent ocean that fluctuates on all time and space scales and when the signals interact with rough surface and bottom boundaries.

Advances in our understanding of and ability to predict long-range propagation in the ocean therefore go hand-in-hand with advances in our ability to accurately describe the ocean environment through which the acoustic signals propagate, whether from concurrent measurements or accurate models or both. For many years following World War II progress in underwater acoustics was impeded by the inability of physical oceanographers to provide meaningful and acoustically useful descriptions of the ocean and its variability. This state of affairs did not prevent a great deal of effort from going into underwater acoustics because of its strategic importance, but the ocean acoustic and physical oceanographic communities drifted apart, to the detriment of both. In addition to deterministic descriptions of the ocean through which the acoustical signals propagate, statistical descriptions of its variability are required to predict acoustical fluctuations. A concise statistical description of the deep-ocean internal-wave field did not become available until 1972, when Garrett and Munk published their now famous internal-wave spectrum (Garrett and Munk, 1972). On larger scales, the very existence of the oceanic mesoscale was largely unappreciated until the Mid-Ocean Dynamics Experiment (MODE) in 1973, even though the mesoscale was subsequently found to contain roughly 99% of the kinetic energy in the ocean (see, e.g., Robinson, 1983).

In parallel with the (continuing) improvements in our ability to describe the ocean, substantial improvements have been taking place in the instrumentation required to make at sea propagation measurements. Particularly important have been improvements in our ability to make propagation measurements using broadband signals and vertical receiving arrays, so that individual ray and/or modal arrivals can be resolved, as has been done in a sequence of experiments at a variety of frequencies and ranges, including SLICE89, the Heard Island Feasibility Test (HIFT), the Transarctic Acoustic Propagation (TAP) experiment, and the Acoustic Thermometry of Ocean Climate project (including the ATOC Acoustic Engineering Test (AET) and the ATOC/ONR Dual-Frequency Test). The basic scattering physics can then be studied without being obscured in the summation over multiple rays and/or modes that occurs for CW transmissions. Equally important has been development of the capability to make propagation measurements in fixed geometries over extended time periods, so that the acoustic fluctuations at time scales from minutes to months can be accurately characterized. Dramatic advances in the amount of data that can be stored internally in small autonomous receivers and in the computational power available from low-power microprocessors have played a key role in making these types of measurements possible.

The combination of improved measurements of long-range acoustic propagation and of improved characterizations of oceanic variability pose a challenge for theoretical and computational efforts to understand and predict long-range propagation in the ocean. In perhaps the first comprehensive attempt to predict acoustic fluctuations using the Garrett-Munk internal-wave model, Flatté *et al.* (1979) used path integral methods, which provide predictions of the acoustic fluctuations to be expected for resolved ray arrivals. Subsequent research included substantial efforts to understand the connections between long-range acoustic propagation through a fluctuating ocean and dynamical system theory (chaos). The steadily increasing computational power available to the ocean acoustic community is now making it possible to carry out broadband simulations of propagation through internal-wave and mesoscale ocean variability using Monte Carlo methods. These calculations have been done using 2-D and 3-D propagation codes, utilizing parabolic equation, geometrical optics, and coupled-mode approaches.

The goals of this Workshop were to assess the current state of our understanding of the propagation and scattering of sound transmitted over several hundred to several thousand kilometers given the developments briefly summarized above, to identify the fundamental outstanding issues remaining, and to identify research opportunities to improve our understanding of long-range propagation. Long-range propagation differs from shallow-water propagation in that bottom interactions are largely unimportant, except near bottom-mounted sources and receivers. Although surface reflections can be important at long range, rough surface scattering is generally not of critical importance at the low acoustic frequencies that propagate long distances. The Workshop therefore focused largely on volume scattering issues and signal coherence (Section 3). Characterization of the ambient noise field is of course equally critical in many applications, but was not the principal focus of the Workshop (Section 4). Advanced signal processing techniques such as matched field processing require that the medium through which the acoustic signals propagate be accurately characterized. Acoustic remote sensing methods have the potential to help do so (Section 5). Section 6 is the heart of this report, summarizing the research opportunities available to improve our fundamental knowledge of long-range propagation.

3. SIGNAL COHERENCE

Ocean processes that reduce the temporal and spatial phase coherence of signals that propagate over long ranges in the ocean impose fundamental limits on what can be achieved using advanced signal processing techniques, including matched field processing and other adaptive array processing methods. The ultimate limits to array size, for example, are set by the vertical and/or horizontal coherence of the received signal. *The fundamental limits to phase-coherent processing at long range are not known at this time and may allow substantially greater processing gains than once thought.*

Internal-wave-induced sound-speed fluctuations are known to be the dominant ocean process causing volume scattering at long ranges. Understanding the basic physics of the scattering of resolved ray and/or modal arrivals is the first step in designing optimum signal processing schemes to fully exploit the coherence of the medium, even in more complex propagation situations. A great deal of progress has been made in understanding this scattering, including both measurements and predictions, but a substantial number of issues remain:

(i) Experimental measurements of the full 3-D wave front coherence (horizontal, vertical, and temporal) of resolved ray and/or modal arrivals are sorely lacking. The North Pacific Acoustic Laboratory (NPAL) experiment is a substantial effort in this direction, but is limited to a single range and frequency band. Further efforts aimed at adequately characterizing the full 3-D wave front coherence will certainly be needed.

(ii) The dependence of internal-wave-induced scattering on range, acoustic frequency, and signal bandwidth has not been adequately determined experimentally. Does the propagation become fully chaotic beyond some range that is a function of frequency? Is there a frequency threshold below which internal-wave-induced scattering becomes unimportant? Theoretical calculations and limited experimental data (Dual-Frequency Test) suggest that internal-wave-induced scattering no longer plays a significant role in reducing coherence at acoustic frequencies below approximately 30 Hz, but further measurements are needed to adequately characterize this regime. The essential argument is that at these very low frequencies the internal-wave-induced phase fluctuations are much smaller than one cycle and so do not affect signal coherence. Other processes, such as surface or bottom scattering, may then become relatively more important, especially at very low frequencies where the acoustic modes extend over a significant part of the water column.

(iii) The Garrett-Munk (GM) internal-wave model provides a surprisingly good characterization of the internal-wave field in and below the main thermocline for use in acoustic scattering calculations. Characterization of the near-surface ocean (sound-speed) fluctuations is much more difficult, however. Near-surface oceanic variability definitely does not have a GM spectrum. It is not obvious that a quasi-universal spectrum exists that will prove adequate or that a spectral description is even appropriate for what may be an highly intermittent process.

(iv) The path integral theory (Flatté *et al.*, 1979) is a geometric optics approximation that predicts the fluctuations and coherence of resolved ray arrivals. Corresponding theoretical results are so far largely unavailable to predict the fluctuations and coherence of resolved modal arrivals, although there has been some work reported in the Russian literature.

(v) Although volume scattering has received most of the attention for long-range propagation, bottom interactions near bottom-mounted sources and/or receivers may significantly limit coherence compared to what it would be for purely refracted or refracted-surface-reflected paths. It may prove important to include vertical apertures in future receiving systems to reduce these effects. Bottom interactions will also have a substantial effect on the modal excitation spectrum for bottom-mounted sources. There are few measurements that have been designed to isolate the effects of bottom interactions near sources and/or receivers. Broadband propagation codes that include shear waves for comparison with such measurements still need substantial development.

4. AMBIENT NOISE

Ambient noise structure and variability were not discussed extensively during the Workshop, but are nonetheless critically important in many applications (including Naval applications) of long-range propagation. Ambient noise at the low frequencies of interest for long-range propagation is dominated by shipping and marine mammals. Wind and wave-breaking processes generally play a lesser role. The implication is that the noise field at low frequencies can be expected to have substantial intermittent structure ("granularity") that can in principle be exploited by appropriately designed receiving systems and signal processing techniques for detection and localization purposes. The fundamental limits to signal processing at long-range are determined as much by the ability of advanced adaptive array processing methods to capitalize on the three-dimensional character of the noise field as by the 3-D coherence of the signal. *The extent to which advanced adaptive array processing methods can exploit the structure of the ambient noise field to achieve improved signal-to-noise ratios at long ranges is unknown, but may be substantial.*

Adaptive noise rejection methods in combination with suitably designed receiving arrays may be able to exploit the structure of the noise field to achieve substantially better than the $10 \log N$ array gain to be expected for a perfectly coherent signal in an isotropic noise field. The essential idea is that individual ships can perhaps be considered as isolated signal sources, rather than as contributors to an overall background ambient noise level, when the receiving array is sufficiently large. (One person's noise is another person's signal.) The implication is that the adaptation efficiency will then depend on the propagation environment and its variability. If sufficient *a priori* information is available to allow accurate predictions of the propagation, then the number and location of both targets and interferers can be treated as unknowns, giving a relatively small parameter space to search.

In spite of the large potential gains that might be made by exploiting the properties of the noise field, its variability and structure have been remarkably poorly characterized:

(i) Even the most basic statistics of the ambient noise field, the probability density functions of noise intensity as a function of frequency, have on the whole not been adequately measured, in spite of their importance for the design of acoustic systems and the accurate prediction of the performance to be expected. The variability of the probability density function of noise intensity on ocean-basin scales remains to be characterized.

(ii) Experimental progress in determining the extent to which the structure of the ambient noise field can be exploited to achieve improved signal-to-noise ratios has been hampered by the difficulty of constructing adequate receiving arrays to fully characterize the spatial and temporal structure of the noise field.

5. OCEAN CHARACTERIZATION

Advanced signal processing techniques such as matched field processing require that the medium through which the acoustic signals propagate be accurately characterized. The focus of the Workshop was on long-range propagation, rather than on the methods used to characterize the medium. Mapping the evolving, large-scale, ocean sound-speed field by making point measurements from ships and/or airplanes is difficult, however. The ocean changes more rapidly than it can be characterized. *Acoustic remote sensing methods have the potential to help characterize the propagation environment for use by advanced signal processing techniques by making it feasible to rapidly and repeatedly measure the sound-speed field over large ocean volumes.*

Ocean acoustic tomography has played a dual role, both providing a tool to help characterize the ocean on large scales *and* helping to stimulate an improved understanding of long-range propagation. A full and complete understanding of the forward problem is the *sine qua non* of any inverse problem. The fields of acoustical oceanography and underwater acoustics both strongly complement and mutually depend on each other.

Acoustic remote sensing methods have the additional virtue of naturally being most sensitive to the environmental properties that are needed to predict acoustic propagation. One potential application is to use tomographic methods to map the ocean over large areas with mesoscale resolution on a routine basis, for example, so that the effect of mesoscale-induced sound-speed fluctuations on signals received on very large arrays can be removed. Development of methods to assimilate acoustic (and other) data into ocean general circulation models (OGCM's) to generate the best possible nowcasts is currently an area of intensive research. Assimilation methods combine both current and previous data in a dynamically consistent manner to interpolate between times and locations for which data are available.

Ocean acoustic tomography has largely focused on the deterministic part of the field. The boundary between deterministic and statistical descriptions of the ocean environment is partly a function of the tools available to characterize the environment, however. The description of the ocean on gyre scales will almost certainly need to be deterministic for purposes of predicting acoustic propagation. At the other extreme, it is difficult to imagine that the description of the oceanic internal-wave field used to make long-range propagation calculations will ever be anything other than statistical in nature (with the possible exception of the coherent part of the internal tides). The description of the ocean mesoscale and its impact on long-range propagation can be either statistical or deterministic, however, depending on the measurement tools available. An area of active research is the inversion of the statistical properties of the acoustic signals received at long range to obtain a stochastic description of the environment, such as internal-wave strength and other parameters describing the spectrum of internal waves.

There are a large number of other existing and emerging opportunities for acoustic remote sensing of the ocean environment, on both large and small scales. Smart and Voronovich (1994) provide a good summary.

6. RESEARCH OPPORTUNITIES

A number of specific research opportunities in long-range propagation are summarized below. Any such list is unavoidably incomplete, of course. The opportunities are organized under the headings

Theoretical, Computer Simulations and Modeling, and Experimental, although there is considerable interaction and overlap between the various categories. The distinction between theoretical opportunities and those involving computer simulations and modeling is perhaps particularly unclear. Finally, we argue that a long-term Ocean Acoustic Observatory is needed to resolve issues that are too large to be addressed by a single investigator or experimental group.

Theoretical

- Existing analytical theories (e.g., Flatté *et al.*, 1979) do not seem to adequately explain the degree of scattering observed for near-axial energy over long ranges, although computer simulations using both parabolic equation and geometrical optics codes give results similar to those observed. This discrepancy needs to be resolved.
- The ATOC Acoustic Engineering Test (AET) gave the surprising result that steep ray arrivals at over 3000-km range behave as though they are on the boundary between the unsaturated and partially saturated propagation regimes, rather than fully saturated as anticipated from Λ,Φ calculations. The observed pulse-time-spread, in particular, is two orders of magnitude smaller than predicted by path-integral theory. These results need to be understood. One suggestion is that the diffraction parameter, Λ, defined for CW transmissions may no longer be appropriate for broadband transmissions and that a fully broadband theory is needed.
- The path integral theory (Flatté *et al.*, 1979) is a geometric optics approximation that predicts the fluctuations and coherence of resolved ray arrivals. Corresponding theoretical results are needed to predict the fluctuations and coherence of resolved modal arrivals. Dozier and Tappert (1978a,b) provide one of the few treatments in the English-language literature of the fluctuations of resolved normal modes, but they only give predictions for modal intensity fluctuations. There has been some work on cross-modal coherence functions in the Russian literature, but we are unaware of any comparisons between theory and measurement.
- The behavior of finite frequency wave fields which, in the ray limit, exhibit chaotic behavior needs to be better understood. It is now widely appreciated that in generic range-dependent ocean environments, most ray trajectories exhibit chaotic behavior, i.e., extreme sensitivity to initial conditions and parameters that describe the environment. The extent to which this extreme sensitivity carries over to finite frequency wave fields is not well understood, however. The marriage of modern ideas relating to chaos in Hamiltonian systems with more traditional approaches to the study of wave propagation in random media holds much promise. The combination of these ideas has the potential to give critical insight into the practical and important problem of understanding the limitations of predictability of underwater sound fields.
- Inversions of acoustic fluctuation data for stochastic properties of the medium (e.g., internal-wave strength) often cannot use conventional linear inverse methods because the unknowns are positive definite (e.g., variances), and so least square methods do not apply. Development of methods for stochastic inversions is needed.

Computer simulations and modeling

- Computer simulations of internal-wave-induced scattering of broadband signals at long range have been done in 2-D, but broadband 3-D propagation codes and fully 3-D internal-wave models have not yet been used to make convincing estimates of 3-D wave front coherence.
- There is a "universal model" (i.e., the Garrett-Munk internal-wave spectrum) for oceanic fluctuations in and below the main thermocline. A similar model is needed to characterize near-surface variability.

There is no guarantee that a universal model exists for near-surface variability or that a spectral description is even appropriate for what may be an highly intermittent process. It may prove necessary to use a model that includes geographical and/or temporal (e.g., seasonal) variability from the outset.

- Computer simulations of acoustic fluctuations have been made using the Garrett-Munk internal-wave spectrum, but the sensitivity of the predictions to the spectral form is unknown. This issue may become particularly acute for scattering from near-surface fluctuations or when inversions for internal-wave spectral parameters are made.
- Computer simulations of mesoscale-induced scattering need to be done using the spectral model(s) of the ocean mesoscale that have recently become available from the interpretation of satellite altimeter data.
- Our ability to make accurate predictions of propagation involving bottom-mounted sources and/or receivers is relatively primitive. Better broadband propagation codes that include shear waves are needed.
- Work is needed on fully stochastic propagation modeling, as opposed to Monte Carlo simulations of propagation through a fully structured ocean sound-speed field.
- Considerable progress has been made in recent years on the development of accurate, wide-angle parabolic equation codes with broadband capabilities. Such codes are invaluable tools for solving the forward problem. Unfortunately, no computationally efficient technique to use the output of such a code to solve the inverse problem (i.e., to find the wave analog of an eigenray) has yet been developed.

Experimental

- The frequency and range dependence of acoustic scattering needs to be fully characterized for broadband transmissions. Neither the ultimate limits to coherence in the ocean nor the ultimate range/frequency limits for tomographic transmissions are known. The ATOC Acoustic Engineering Test, for example, gave the remarkable result that steep ray arrivals are scattered surprisingly little and, as a result, have remarkably high coherence. In contrast, the SLICE89 experiment suggested that near-axial arrivals are scattered more than might have been expected based on predictions of path-integral theory. The transition as a function of range from resolved rays to near-axial arrivals that are highly scattered needs to be quantified and understood. The Dual-Frequency Test strongly suggested that internal-wave-induced scattering is significantly reduced at frequencies below about 30 Hz. The North Pacific Acoustic Laboratory (NPAL) experiment will almost certainly raise almost as many questions as it answers about 3-D coherence. Although it represents a significant advance, it still only provides data for one frequency and one range, for a limited, sparse aperture. Follow-on experiments will be needed once the NPAL data have been digested.
- Previous experiments have hinted that phase stability is high even in regimes for which large amplitude fluctuations are observed, in apparent contradiction to the predictions of path integral theory. Continuous, broadband transmissions lasting for order 1–2 weeks are needed to investigate the suspected discrepancy. It would be ideal to use transmissions to a vertical line array receiver so that the phase stability of both resolved rays and modes could be investigated simultaneously. Such an experiment, having a densely-filled vertical line array and a fast effective pulse transmission rate, would also provide data on the temporal and vertical variability of the fluctuations observed in SLICE89 that could only be characterized as broadband because of inadequate sampling.
- Few measurements of cross-modal coherence have been made. Installation of a vertical array of low-frequency *sources* capable of exciting selected individual modes together with VLA receivers

capable of resolving the modal structure of the received signal at several ranges would dramatically improve our understanding of modal scattering and cross-modal coherences.

- Non-geometric acoustic arrivals have been observed on SOSUS arrays located many wavelengths below the lower-turning-point depths of the geometric rays. These arrivals are apparently associated with caustics, but attempts to explain them in terms of classical diffracted energy or in terms of internal-wave and mesoscale scattering have so far been unsuccessful. They have been observed in a number of experiments and appear to be quite common. They may be important in the design of both active and passive systems. Installation of a full-ocean-depth VLA in the vicinity of a deep SOSUS array would help us understand these arrivals.
- There are few measurements that have been designed to isolate the effects of bottom interactions near sources and/or receivers. Installation of a VLA in deep water near a bottom-mounted source would provide important data on the modal excitation spectrum and provide a critical test for propagation codes that include shear waves.
- Scattering by the ocean mesoscale, fronts, etc., has received little attention to date, with experimental efforts using broadband transmissions predominately devoted to understanding internal-wave-induced scattering in regions where strong fronts are not expected. We do not know, for example, if it would it be possible to correct for mesoscale induced variability on a very long (100 km, say) horizontal array.

Ocean Acoustic Observatory

The size of the receiving arrays required to measure and exploit signal coherence and the structure of the noise field are too large to be installed by a single investigator or experimental group. An *Ocean Acoustic Observatory* is needed to allow the requisite 3-D aperture to be assembled over time, as funding permits. A dynamic, evolving Observatory is envisioned, consisting of a combination of horizontal and vertical receiving arrays, whose design and implementation would change as our understanding and needs evolve. The underlying enabling technology would be one or more fiber-optic cables to connect the array site to shore. The cables would provide power to the receiving systems for long term operation. The very large bandwidth available to return data to shore would make it possible to have much larger apertures than previously realized. One approach would be to terminate the cables in junction boxes to provide the needed flexibility for an evolving array geometry. A fixed site would allow the study of variability over seasonal and longer time scales.

Such an Observatory would not only serve to advance our understanding of long-range propagation and the structure of the ambient noise field, but would also provide invaluable data on the geophysical and biological processes that contribute to ambient noise, including undersea earthquakes and volcanic eruptions, marine mammal vocalizations and distributions, and surface processes such as rain and wind. As one component of an active tomographic system, an Observatory would also provide data on ocean thermal and current structure.

The idea of an Ocean Acoustic Observatory is not new. Professor Walter Munk first proposed the idea nearly two decades ago, on the occasion of the fiftieth anniversary of the Woods Hole Oceanographic Institution in 1980. The Panel on ONR Research Opportunities in Underwater Acoustics of the Naval Studies Board argued eloquently for an Ocean Acoustic Observatory in their 1990 report. Efforts toward Ocean Acoustic Observatories based on the existing SOSUS system have been made by the Naval Postgraduate School and by the Ocean Acoustic Observatory Federation (recently assembled with funding from the National Ocean Partnership Program). The NPAL and Full-Field Program (FFP)

arrays currently in place are differing approximations to the Observatory that is required. But the need for a dedicated site to improve our understanding of the 3-D structure of the signal and noise fields in the deep ocean remains.

Subsequent to the Workshop reported on here, the JASON Advisory Group studied the utility of an ocean acoustic observatory and endorsed the concept pending in depth analysis. As a result, ONR commissioned a Phase I Study of the concept which also supports the implementation of an observatory.

Summary

The specific recommendations developed at the Workshop are fully consistent with more general recommendations recently made by the Panel on Undersea Warfare, Committee on Technology for Future Naval Forces, Naval Studies Board (1997). The goal of the Panel was to develop a LIMITED list of research opportunities that hold the greatest promise of increasing fundamental knowledge and, at the same time, aiding the Navy in carrying out its mission. Their recommendations were in part:

Highest-level Recommendations:

- Establish and maintain a dedicated long-term program, centered on at-sea measurements and tests, to provide the science and technology bases for pushing active and passive acoustic array gain to the limits imposed by the ocean. Decades of experience have shown that advances in ASW come about only as a result of such programs.

Recommendations for Follow-on Action:

- Determine the limits of acoustic concepts such as coherent and matched-field processing with volumetric (both horizontal and vertical) arrays through comprehensive environmental measurements, accompanied by modeling and testing.
- Use SOSUS data to explore ocean coherence and other acoustic phenomena that will be fundamental to the next generation of sonar technology.

REFERENCES

Dozier, L. B., and F. D. Tappert (1978). Statistics of normal mode amplitudes in a random ocean. I. Theory, *J. Acoust. Soc Am.*, **63**, 353–365.

Dozier, L. B., and F. D. Tappert (1978). Statistics of normal mode amplitudes in a random ocean. II. Computations, *J. Acoust. Soc Am.*, **64**, 533–547.

Flatté, S. M. (Ed.), R. Dashen, W. H. Munk, K. M. Watson, and F. Zachariasen (1979). *Sound Transmission Through a Fluctuating Ocean*. Cambridge Univ. Press, Cambridge, England, 299 pp.

Garrett, C. J. R., and W. H. Munk (1972). Space-time scales of internal waves, *Geophys. Fluid Dyn.*, **2**, 225–264.

Lynch, J. F. (1997). Report on the Office of Naval Research Shallow-Water Acoustic Workshop, 1–3 October 1996. Woods Hole Oceanographic Institution Technical Report WHOI-97-12, June 1997.

Panel on Research Opportunities in Underwater Acoustics, Naval Studies Board, Commission on Physical Sciences, Mathematics, and Resources, National Research Council (1986). Research Opportunities in Underwater Acoustics. National Academy Press, Washington, D. C., June 1986.

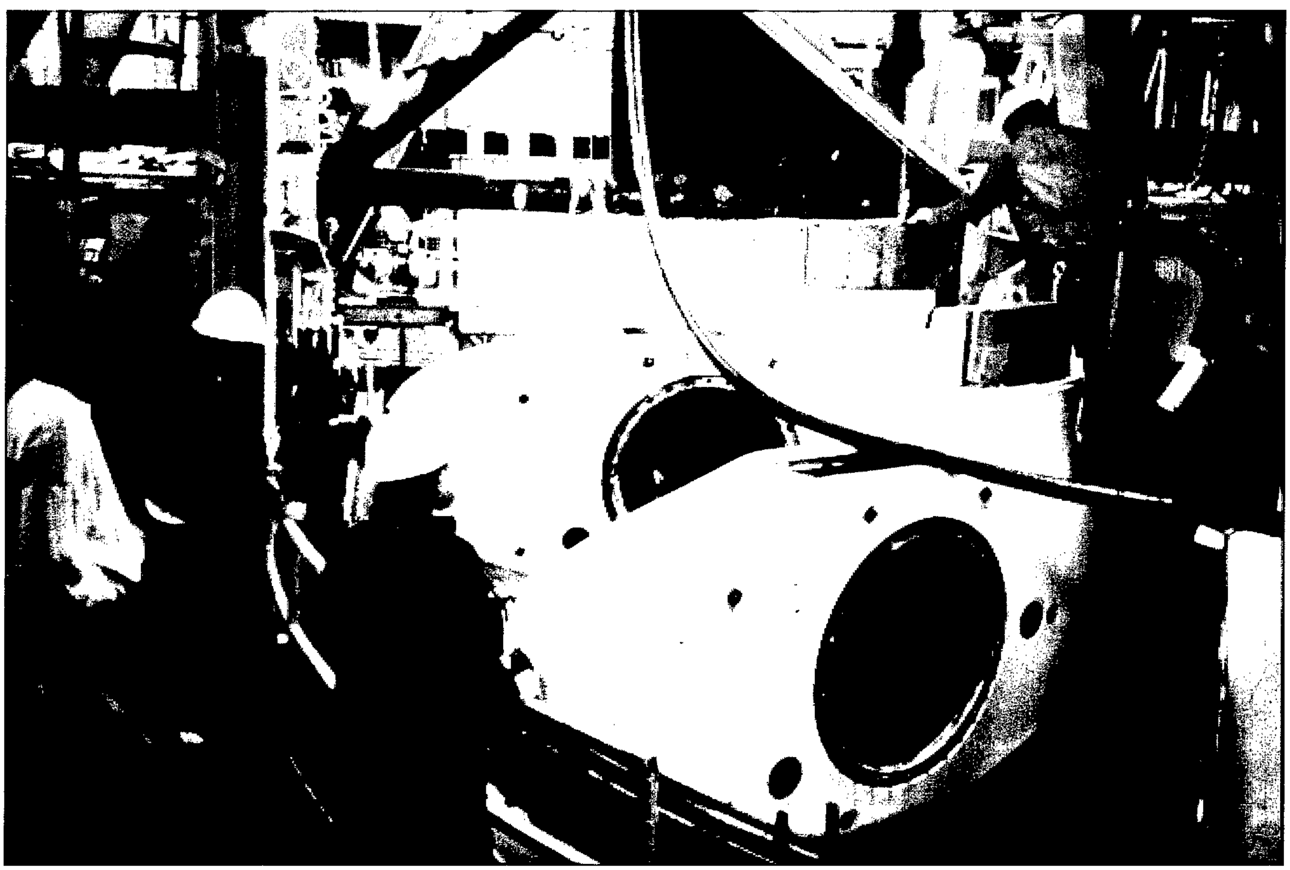
Panel on ONR Research Opportunities in Underwater Acoustics, Naval Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council (1990). Research Opportunities in Underwater Acoustics. National Academy Press, Washington, D. C.

Panel on Undersea Warfare, Committee on Technology for Future Naval Forces, Naval Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council (1997). Technology for the United States Navy and Marine Corps, 2000–2035: Becoming a 21st-Century Force. Volume 7. Undersea Warfare. National Academy Press, Washington, D. C.

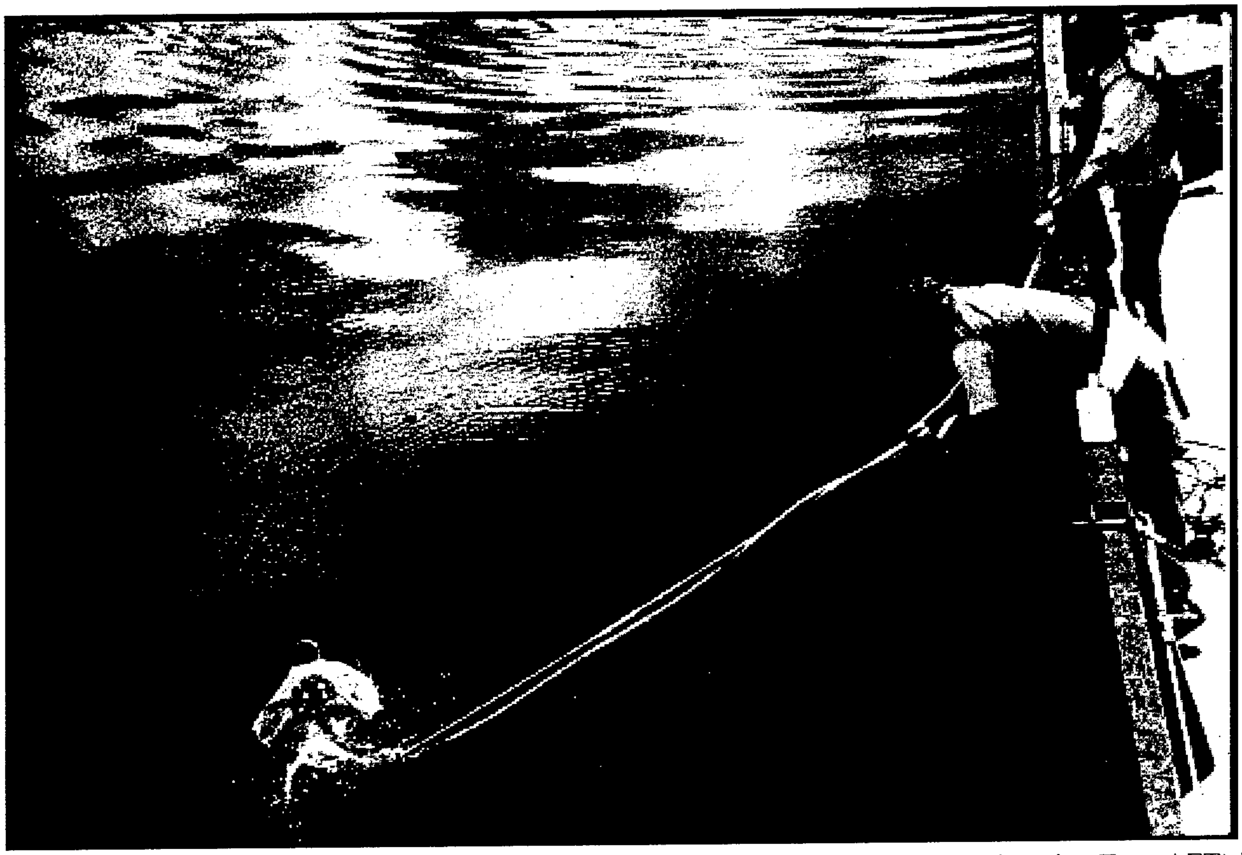
Robinson, A. R., Ed. (1983). *Eddies in Marine Science.* Springer-Verlag, Berlin, Germany, 609 pp.

Smart, R., and A. Voronovich, Editors (1994). Acoustic Techniques for Measuring Ocean Variables, A Review of Existing and Emerging Opportunities. NOAA Office of Oceanic and Atmospheric Research, Washington, D.C.

Thorsos, E. I. (1997). Report on the Office of Naval Research High-Frequency Acoustics Workshop, 16–18 April 1996. Applied Physics Laboratory, University of Washington Technical Report APL-UW TR 9702, June 1997.



Matthew Dzieciuch, left, inspects the HLF-4LL acoustic sources aboard the R/V *Cory Chouest* at Heard Island during January, 1991.



Recovery of a pop-up buoy from the R/V *New Horizon* during the ATOC Acoustic Engineering Test (AET) in September, 1994.

Daniel Doherty assists while John Kemp handles special VLA cable during deployment of an NPAL mooring from the R/V *Melville* during July, 1998.

Appendix A

ONR Long-Range Propagation Workshop

Attendees

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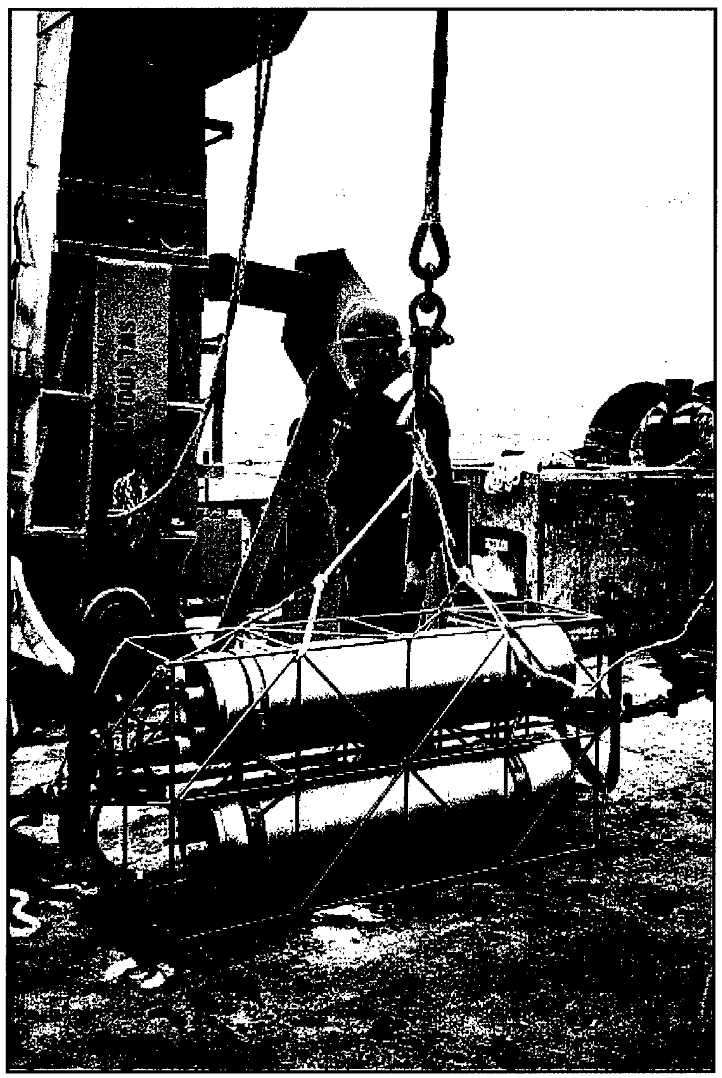


Peter Worcester stands by as an NPAL acoustic receiver is readied for deployment on the R/V *Melville* during July, 1998.

Appendix B

ONR Long-Range Propagation Workshop

Agenda

Facilitator: Peter F. Worcester

Monday, March 3

0830–0840	Peter Worcester	Introductory remarks and logistics
0840–0850	Jeffrey Simmen	ONR Perspective

Measurements

0850–0910	Bruce D. Cornuelle and the ATOC Group	A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean
0910–0930	James A. Mercer, Bruce M. Howe and Robert C. Spindel	Ocean Acoustic Transmit System (OATS)
0930–0950	Ted Birdsall and Kurt Metzger	Simultaneous dual frequency band measurements: Internal wave effects and mode compression
0950–1010	Matthew Dzieciuch and the ATOC Group	The coherence of wavefronts in ATOC experiments
1010–1020	**Break**	
1020–1040	Brian Dushaw	"Ray-like" arrivals in the shadow-zone of megameter range acoustic transmissions

Propagation Modeling

1040–1100	Mike Collins	Long-range propagation modeling
1100–1120	Arthur B. Baggeroer, Henrik Schmidt, and Brian Sperry	Mode Excitation for a source on a rough, elastic, sloping bottom
1120–1140	E. C. Shang, Y. Y. Wang, and A. G. Voronovich	Modal degeneration, scattering and horizontal refraction in frontal zone
1140–1200	Ralph A. Stephen	Propagation issues in marine seismology and geoacoustics
1200–1300	**Lunch**	

Internal-Wave-Induced Scattering

1300–1320	Stanley M. Flatté and Galina Rovner	Path-integral predictions of travel-time variance due to internal waves for multimegameter propagation
1320–1340	Michael G. Brown	Stochastic ray theory for long-range sound propagation in deep ocean environments

1340–1400	Tim Duda	Secondary effects in the wavefront arrivals
1400–1420	John Colosi	Oceanographic issues for long-range acoustic propagation in the ocean
1420–1440	B. Edward McDonald	Wavefront smearing and internal waves in the deep ocean
1440–1500	Kevin D. Heaney and W. A. Kuperman	Extracting information from long range ocean acoustic signals
1500–1510	**Break**	

Mesoscale-Induced Scattering

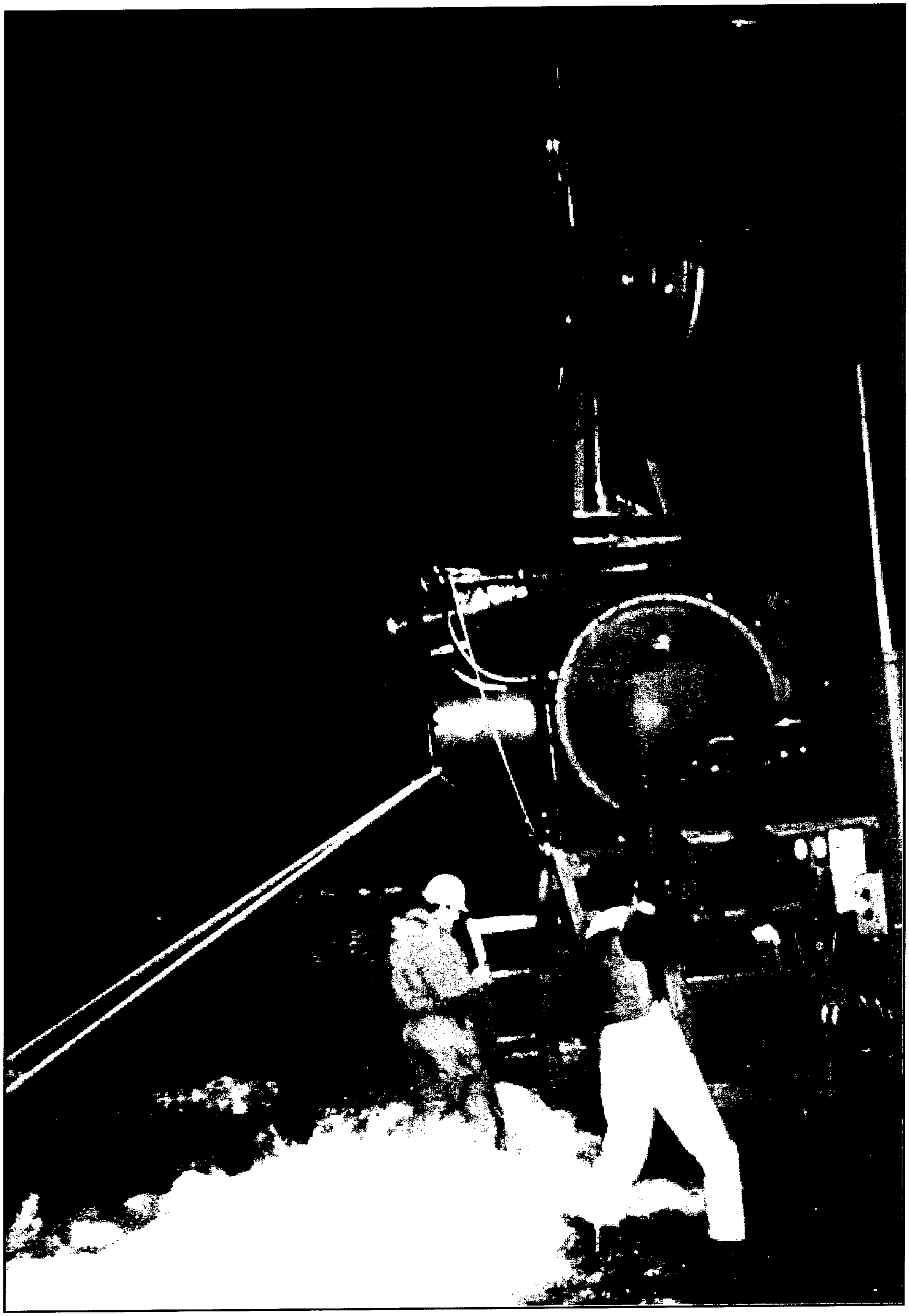
1510–1530	F. D. Tappert	Travel time effects of ocean mesoscale structure at global ranges
1530–1550	Amy R. Smith, Kevin B. Smith, and Ching-Sang Chiu	Modal travel time variability through the California Current
1550–1610	Michael A. Wolfson	Wave chaos demonstrated by full wave, broadband simulations through an adiabatic ocean
1610–1630	A. G. Voronovich and E. C. Shang	Horizontal-refraction-modal tomography with mode interactions

Future Field Work

1630–1650	Peter Mikhalevsky	Arctic Climate Observations Using Underwater Sound (ACOUS)
1650–1710	John Spiesberger	New directions in understanding acoustic propagation and tomography at basin-scales
1710–1730	Peter F. Worcester and Robert C. Spindel	North Pacific Acoustic Laboratory

Tuesday, March 4

0830–1000	Plenary Discussion	Future Field Work
1000–1020	**Break**	
1020–1200	Working Group Discussions	Research Issues in Long-Range Acoustic Propagation
1200–1315	**Lunch**	
1315–1335	Group 1 report	
1335–1355	Group 2 report	
1355–1500	Plenary Discussion	Research Issues in Long-Range Acoustic Propagation
1500–1520	**Break**	
1520–1700	Plenary Discussion	Research Issues in Long-Range Acoustic Propagation (cont.)



Recovery of an HLF-6A acoustic source (28 Hz and 84 Hz) on the M/V *Independence* during the Dual-Frequency Test in July, 1996.

Appendix C

ONR Long-Range Propagation Workshop

Abstracts

March 3, 1997

Measurements

0850

A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean

Bruce D. Cornuelle and the ATOC Group*
Scripps Institution of Oceanography, University of California at San Diego, La Jolla, California 92093

Broadband acoustic signals were transmitted from a 75-Hz source suspended near the depth of the sound channel axis to a moored vertical array of 20 hydrophones approximately 3250 km distant in the eastern North Pacific Ocean during November 1994. The receiving array extended in depth from 900 to 1600 m. A nearly concurrent estimate of the sound-speed field between the source and receiver was made using expendable bathythermograph (XBT) and expendable conductivity-temperature-depth (XCTD) data. The early part of the arrival pattern consists of ray-like arrivals, evident as wave fronts sweeping across the array, which can be identified with specific acoustic rays using any of several ocean climatologies. The time-mean travel times of the arrivals are inconsistent with predictions based on the sound-speed field constructed using the XBT/XCTD measurements, however, suggesting that the equation used to compute sound speed from temperature and salinity requires refinement. Scattering from internal-wave-induced sound-speed fluctuations causes the later part of the arrival pattern to be confused and unstable, with the times at which the acoustic reception ends (the pulse termination) at off-axis receivers occurring significantly later than predicted neglecting internal waves. Linear inversions using the ray travel times together with the time of the near-axial pulse termination indicate that the range-averaged ocean temperature in the vertical plane connecting the source and receiver can be determined with an uncertainty of about 15 millidegrees and that the trend in temperature over a week can be determined with an uncertainty of about one millidegree/day. Vertical resolution is concentrated near the ocean surface (and at the corresponding conjugate depths), however, because all of the resolved ray arrivals have upper turning depths within a few hundred meters of the surface.

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0910

Ocean Acoustic Transmit System (OATS)

James A. Mercer, Bruce M. Howe and Robert C. Spindel
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The Ocean Acoustic Transmit System (OATS) is a portable suite of hardware for conducting long-range underwater acoustic experiments. OATS was designed to be placed on ships of opportunity and includes its own handling system. The handling system is mounted on a skid structure and incorporates a lifting frame, capture head, umbilical winch, and hydraulic power

and control unit. The skid also stores two (one spare) modified HLF-6A transmitters. The modified transmitters and the electro-optical-mechanical umbilical allow transmissions to depths of 1300 meters. The system is capable of source levels well in excess of 200 dB (re 1 ÊP @ 1 m) over the frequency range of 40 to 150 Hz. OATS was developed by the US Navy to specifications provided by the Applied Physics Laboratory, University of Washington (APL-UW) in support of the Joint Environmental Test Initiative. The system has been transferred to APL-UW and is available for collaborative efforts with other researchers. This presentation will include a description of the OATS and results from the ONR sponsored Alternate Source Test in which OATS was used at 28 and 84 Hz simultaneously.

0930

Simultaneous dual frequency band measurements internal wave effects and mode compression

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Kurt Metzger

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The July 1996 Alternate Source Test (AST), conducted by SIO, APL U/W and UMich used a unique signal spanning 19 to 93 hertz to compare propagation, especially the internal wave degradation. Simultaneous m-sequence signals centered at 28 and 84 hertz were transmitted to ATOC Vertical Line Arrays and Naval Facilities. This presentation emphasizes three points relevant to long range acoustic propagation.

1) VLA ray arrival results at 3.5 and 5 Megameters clearly show critical internal wave sensitivity at these ranges and frequencies, and unquestionably demonstrate the value of simultaneous dual-band measurements.

2) Source manufacturers and signal processors have to work together to achieve the necessary low frequency multi-octave transmissions.

3) Mode compression signal processing promises mode results with the same time resolution as with ray processing.

0950

The coherence of wavefronts in ATOC experiments

Matthew Dzieciuch and the ATOC Group*
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In tomography experiments, acoustic ray travel time measurements are the data from which dependent oceanographic variables (such as heat content, current, etc...) may be inferred. The travel times therefore set the precision of the experiment and so it is important to make estimates of the travel time variance. Coherent integration (in time and space) is typically used to increase signal-to-noise ratio and thus the precision. Ambient noise is usually not the limiting factor but the self-scattered energy is the most problematic and limits coherent integration. Examined in detail, rayfronts show variations in time, depth (for a vertical array) and in pulse shape. The scale and strength of these variations were measured during recent ATOC experiments. At up to 5 Mm ranges and frequency ranges from 28 to 84 Hz, coherence times (wander) of >10 minutes, coherence lengths of >500m, and pulse spreads (coherent bandwidth) of <50 ms were the norm. Although the numbers above are preliminary estimates, the basic result is clear, the coherence is good enough to permit long integrations (i.e. large SNR gains) in time and depth and therefore the precision of basin scale travel time measurements is adequate to effectively monitor climate.

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1010 Break

1020

"Ray-like" arrivals in the shadow-zone of megameter range acoustic transmissions

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Receptions of long-range acoustic transmissions by deep hydrophone arrays in the eastern Pacific and western Atlantic often have "ray-like" arrivals that occur in the shadow zone of the predicted time front. These stable, "ray-like" arrivals can be identified with the cusps, or caustics, of the time front predicted by ray tracing, but the hydrophone arrays lie up to 750 m below the depth of the caustic. The observed acoustic energy is apparently not accounted for by errors in the sound speed field, by leakage of acoustic energy below the caustics as predicted by the full wave equation, or by scattering due to internal waves. Data obtained during experiments in the Atlantic (ATE'90, AMODE'91 both 250 Hz) and in the Pacific (AET'94-75 Hz, ATOC-75 Hz, AST'96-28 and 84 Hz) will be reviewed. Tidal variability is apparent in the data obtained in the Atlantic. These peculiar data present a number of problems: Does this data type ever occur above the time front? If the raypaths are wandering all over the water column, as might be implied by the existence of these shadow-zone arrivals, why are predictions of ray travel times usually accurate? What quantities can better define how "ray-like" these arrivals are? What is the energy loss associated with these data, and how does this loss increase the attenuation of very long-range acoustic transmissions? How can we invert these data for oceanographic variables when we cannot do the forward problem? Only the shadow knows....

Propagation Modeling

1040

Long-range propagation modeling

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This presentation will discuss some recent work in long-range propagation modeling. Efficient techniques based on the PE method and normal modes have been developed for efficiently solving long-range problems in both two and three dimensions. Ray chaos and its implications (or nonimplications) have also been of interest. [Collaborators include A. T. Abawi, W. A. Kuperman, J. F. Lingevitch, and W. L. Siegmann.]

1100

Mode Excitation for a source on a rough, elastic, sloping bottom

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In the ATOC program the source was sited on a slope at a depth of the SOFAR axis so that the signal would excite the axial modes efficiently for long range propagation. One of the important issues was the elevation off the source off the seafloor.

Buoying it on a mooring into the water column presented significantly more engineering challenges than simply resting it on platform on the seafloor. We examine the impact upon the mode excitation spectrum of the source depth on a rough, elastic sloping bottom using a range dependent OASES code. This code matches vertical wavenumbers across range independent sectors, which may include interface roughness, as it steps out in range. It has been very successful in modeling the related problem of the effect of epicenter depth for T phase excitation on a sloping bottom. (Sperry, et al (JASA 100(5)).

We use a Munk sound speed profile with a minimum at 1000 m and a sloping bottom out to a range of 30 km after which the bottom depth is constant. We project the field onto the depth dependent modes to determine their excitation. We also examine the group delays to determine the impact on travel times. Initial results suggest that even a modest (100 m) elevation concentrates the power in the low order modes. In addition to the source elevation the slope gradient and roughness and the elastic properties of the bottom are important parameters.

1120

Modal degeneration, scattering and horizontal refraction in frontal zone

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The frontal effect is crucial for long-range acoustic propagation. The adiabaticity of modal propagation is, most likely, no longer valid in frontal zone. Numerical simulation of acoustic propagation through frontal zone has been conducted for two types of ocean front.

(1). The Sub-Arctic frontal zone in North Pacific
This frontal zone is the transition from the SOFAR duct to the surface duct near 44.8°N. According to the Semtner-Chervin's model, the cold water at the surface making a secondary duct added to the main SOFAR duct – "double channel." The secondary surface duct is getting colder and colder northward and finally becoming the only main duct. It is found that there are two characteristic ranges in this frontal zone: a). Modal degeneration range r_m^D, and b). Modal scattering range r_m^S. At range r_m^D, mode m and mode n (usually n = m+1) are degenerated, the modal wavenumber of mode m and m+1 are getting equal and then the shape of modal function of mode m+1 is taken by mode m (vise versa), so this is only a "label changing" process and there is no *real repopulation* takes place at this range. At range r_m^S, the modal energy of mode m is scattered to other modes, there is *real* repopulation takes place at this range. Our numerical simulation (65 Hz) illustrates that r_m^D and r_m^S are separated about several hundreds meters apart for lower modes (m<5), and merged for higher modes. Numerical results of the modal scattering matrix $\mathbf{S}_{mn}$ will be reported.

(2). The Polar frontal zone
The Polar frontal zone is known to have the highest contrast between the properties of the divided water masses in Nordic seas. We use a "few parameter model" given by Kuz'kin (1993) to estimate the low frequency (20–150Hz) modal horizontal refraction. The acoustic propagation at 20 Hz is pretty adiabatic, the acoustic diagnostic of the frontal features is discussed.

1140

Propagation Issues in Marine Seismology and Geoacoustics

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Three topics in marine seismology and geoacoustics are relevant to long range propagation in the oceans. 1) Earthquake sources in the deep ocean excite abyssal T-phases which propagate in the sound channel for long distances. T-phases are commonly observed on hydrophone arrays in the sound channel and on seismometers on land near the coast. The mechanism for coupling energy from the seafloor into the sound channel in deep water is poorly understood. Scattering from seafloor heterogeneities and tunneling of evanescent waves have been proposed. 2) Po/So waves through the earth's crust and upper mantle beneath the oceans exhibit nearly constant propagation velocities of 8.0 and 4.6k/s respectively and they exhibit

extremely efficient propagation. Frequencies as high as 20 Hz can be observed to 3300 km range over the deep ocean. Adequately predicting the coda or reverberation in these waves is a challenging task for forward modeling techniques. 3) Controlled source seismic experiments in shallow water give transmission loss results over ranges of 3 km at frequencies between 20 and 100 Hz. Complex frequency dependencies are observed at frequencies below cut-off which are caused by strong lateral heterogeneities at and below the seafloor.

1200 Lunch

Internal-Wave-Induced Scattering

1300

Path-integral predictions of travel-time variance due to internal waves for multimegameter propagation

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Predictions for travel-time spread and wander of timefronts that represent propagation over several megameters in the North Pacific have been calculated with path-integral expressions that are numerically integrated. These expressions have been improved over past usage by accounting for ray curvature in calculations of internal-wave correlation lengths, and by assuring that internal-wave sound-speed variances near the ocean surface are realistically modeled. Sensitivity to environmental uncertainty is treated by doing the calculations for a variety of profiles obtained mainly from the Levitus database. Predictions for bias, vertical coherence lengths, and coherence times will also be presented. These results can be used to transform measurements of travel-time variance into measurements of the ocean internal-wave field; they also provide estimates of the accuracy with which larger-scale tomography experiments can be done. Some preliminary comparisons with observations from the ATOC experiment will be shown in order to provide some understanding of the usefulness of the technique.

1320

Stochastic ray theory for long-range sound propagation in deep ocean environments

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The motion of sound ray trajectories in deep ocean environments, including internal wave induced scattering, is considered. Using the empirical Garrett-Munk internal wave spectrum and results from the study of stochastic differential equations, a framework for studying and modeling stochastic ray motion is developed. It is argued that terms in the ray equations involving internal wave induced sound speed perturbations, delta c, can be neglected, but those involving the depth derivative of delta c cannot. It is then shown that the (Markov) approximation that spatial variations of the depth derivative of delta c are delta correlated is remarkably good. These results lead naturally to an extremely simple system of coupled stochastic ray equations (in ray depth z, ray slowness p and travel time T) in which stochasticity enters the system only through the equation for p. Solutions to the stochastic ray equations — or the corresponding Fokker-Planck equation — describe approximately the density of acoustic energy in range, depth, angle and time. Two dimensionless parameters are introduced: 1) an acoustic Peclet number which is a measure of the ratio of the strength of deterministic ray refraction to that of stochastic scattering induced ray diffusion; and 2) a measure of the ratio of the strength of scattering induced ray diffusion

to that of wave diffraction. Numerical solutions to the stochastic ray equations are compared to full wave simulations. These results show that, even in the weak scattering regime (large acoustic Peclet number), the inclusion of internal wave induced scattering may lead to important qualitative corrections to predictions of distributions of acoustic energy.

1340

Secondary Effects in the Wavefront Arrivals

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Acoustic propagation of a few hundred hertz over a few thousand kilometers in the sound channel has been observed to decay from an organized wavefront structure of early arrivals to a disorganized late crescendo. Some characteristics of the late portion of mode-like energy have been found to be determined by internal gravity waves. Structures predicted using only large-scale ocean characteristics are not observable. Details of the early wavefronts, with ray-like propagation, have also been found to be sensitive to internal waves, but retain many characteristics predictable with only large-scale ocean structure. In this regard, the internal-wave effects are secondary to the wavefront arrivals. The effects include fading, focusing, and timing deviation. In most theories the internal-waves have strongest influence at turning points. One theory relies on the second derivative (with depth) of sound speed, mainly due to internal waves. Another theory, not fully developed, considers the second derivative and the first derivative, so that the sound channel enters. In this theory the effects of internal waves are accentuated in areas of weak sound-speed gradient. Effects include spatial and temporal phase and amplitude variability (loss of coherence). Effects from it may be more variable from ocean to ocean than a pure second-derivative dependence. Also, it may produce erratic strong focused signals that do not seem like perturbations.

1400

Oceanographic issues for long-range acoustic propagation in the ocean

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Internal wave induced sound-speed fluctuations have well documented effects on basin scale transmissions including coherence limitations and travel time biases and variances. The Garrett-Munk spectral model for internal wave displacements has been very useful in numerical modeling and analytic theories for predicting and explaining observations. Yet, for acoustic energy which samples the upper few hundred meters of the ocean the GM model understandably has proven inadequate. Since basin scale transmissions only resolve rays in this category it is important to attempt modifications to the basic GM model; a few alternative models will be presented.

Furthermore, for very long range propagation the mesoscale field becomes a statistical field of interest. Mesoscale fluctuations in sound speed of order 10 m/s with length scales of order tens of kilometers, and time scales of order weeks to months are not uncommon. A realistic spectral model of the ocean mesoscale, derived from 3 years of TOPEX/POSEIDON altimeter measurements, now exists and can be used in acoustic propagation studies. Interesting applications involve the study of 3-D effects, and the prediction of mesoscale induced travel time biases and variances.

1420

Wavefront Smearing and Internal Waves in the Deep Ocean

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Experiments Slice89 and ATOC95 have reported long range pulse receptions containing relatively clean time domain wavefronts early in the coda followed by an excessively smeared- out crescendo near the sound channel axis. (The smearing

out exceeds mode- and frequency- dispersion for prevalent sound speed profiles in a range independent ocean). Numerical simulations by various investigators have compared propagation with and without internal waves present; results have identified internal waves as the cause of the excess time smearing. What can be learned about the ocean from the degree of smearing and its distribution throughout the arrival coda? We examine this question using a ray model plus a linear stability analysis based on Mathieu's equation. Two types of internal wave perturbations are considered and related to wavefront smearing: surface driven internal waves which decrease exponentially with depth below the thermocline, and deep internal waves generated by interaction of inertial currents with bathymetry. Conditions for smearing of the axial arrival are related to the amplitude of the internal wave displacement near the axis, plus its horizontal and vertical correlation scales.

1440

Extracting Information from Long Range Ocean Acoustic Signals

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The ATOC95 experiment was conducted in the winter of 1995 with transmission paths from Pioneer Seamount, off Monterey, to various receivers around the Pacific, including a vertical line array at Hawaii (Range = 3515 km). The experimental bandwidth was 30 Hz with a center frequency of 75 Hz. The early arriving energy (steeply propagating sound) is robust from reception to reception. However, much of the signal shows very little stability from reception to reception (4 hours apart). This variability is commonly thought to be internal wave induced mode coupling. We have addressed the question of what long range information can be extracted from these arrivals.

The ability to localize a source is an indication of the remaining source information in the signal. To access the information in the late arriving energy bundle a mode filter was developed. Using a Bartlett beamformer on received mode amplitudes, the source was successfully located in depth for a portion of the experiment (Acoustic Engineering Test). A mode travel time difference range estimator was developed and shown to be biased by internal wave coupling. We developed a range estimator which matched the received wavefronts with those of predicted wavefronts at various ranges.

In order to understand the effect of the internal waves on acoustic propagation for this environment, a rapid range-dependent forward model was needed. The Frequency Interpolation Parabolic Equation (FI-PE), based upon Collin's FEPE, was developed providing significant speed increases for doing broadband calculations. The algorithm maps single frequency PE results to mode space, allowing frequency interpolation in the complex mode amplitudes. Using FI-PE, we generated a series of predictions with varying internal wave strengths through the ATOC95 environment.

With this ensemble of calculations as a forward model, three different measures where calculated from the data and simulations to do an inversion for the background internal wave strength in the ocean. The observables used where : broadening of the axial cutoff, received modal energy spectrum, and mode arrival time spread. The final two mode space inversions yielded an estimated internal wave strength of 1.8 GM. This is nearly twice that found in SLICE89 by Flatté and Colosi.

1500 Break

Mesoscale-Induced Scattering

1510

Travel Time Effects of Ocean Mesoscale Structure at Global Ranges

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A range-dependent ray trace model and the broadband UMPE model are used to model sound propagation at fixed bearing through a field of mesoscale baroclinic modes in order to study the effects of mesoscale structure on travel time at long ranges. The ray model exhibits chaos at ranges beyond a few Mm as manifested by an exponentially increasing number of triplications of the wavefront. In addition, the ray model predicts a mesoscale travel time bias, in the direction of later time, of the last axial arrival that is about 50-150 ms/Mm. At center frequency 75 Hz and bandwidth 50 Hz, the full-wave UMPE model qualitatively confirms the ray trace predictions of chaos (now called "wave chaos"), and also quantitatively confirms the above mesoscale bias of the last axial arrival. Two theories, rays and modes, based on the adiabatic approximation are used to explain the simulated mesoscale bias in magnitude and sign. The steeper, early ray-like arrivals are relatively stable in the presence of mesoscale structure and should be useful for long-range tomography.

1530

Modal travel time variability through the California Current

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Understanding inherent ocean variability is important when installing "permanent" acoustic transmission systems. In this study, the effects of ocean mesoscale perturbations on modal acoustic travel times are examined for a region where the California current system is expected to be a dominant source for fluctuations in the ocean temperature and salinity fields. Specifically, the chosen acoustic path is between a moored SOFAR source and a SOSUS hydrophone array approximately 475 km distant at Point Sur, California. Input environmental data is obtained from the global Parallel Ocean Circulation Model (POCM), also known as the Semtner and Chervin model. To assess the acoustic stability of arrivals for this source/ receiver combination and the geophysical noise for this particular acoustic path, data sets spanning a one-year time period from the POCM model are used to derive range-dependent sound speed profiles along a great circle path between source and receiver. The UMPE acoustic propagation model is then used to compute the acoustic pressure field and arrival structure at the receiver. To statistically examine the temporal and spatial variability in the arrival times, the computed pressure field is decomposed into local normal modes using the numerical code KRAKEN. Then by using inverse Fourier techniques, the individual modal arrival structures are computed. The temporal, spatial and seasonal variability in the individual modal arrivals of the first thirty modes are assessed. The mesoscale bias variability is examined by comparing the individual modal arrival structure for the range-dependent environment to that of the corresponding range-averaged environment.

1550

Wave chaos demonstrated by full wave, broadband simulations through an adiabatic ocean

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The adiabatic hypothesis is used to derive a parabolic equation in the horizontal plane along the sound channel for each vertical mode. Using an idealized model of mesoscale for deterministic fluctuations of sound speed at the axis depth, broadband numerical simulations are performed at various bandwidths for the lowest acoustic mode. The time fronts at different ranges illustrate how diffractive smearing leads to irresolvability of horizontal multipaths at an exponentially fast rate (in range), until saturation is approached — the range at which the normalized fluctuations in field intensity approach unity. We interpret this as a definition of wave chaos in weakly range dependent environments, and present its connection to the field of wave propagation in random media.

1610

Horizontal-Refraction-Modal Tomography with mode interactions

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A scheme of the acoustical tomography of the ocean based on measurements of horizontal refraction angles has been suggested in [A. G. Voronovich and E. C. Shang, J. Acoust. Soc. Am. 98, 2706-2716 (1995)]. This scheme is designated to infer 3-D internal structure of the ocean of meso- to global scale (up to 1000 km). It is assumed that small values of horizontal refraction angle (HRA) are measured with the help of ocean interferometer consisting of two vertical line mode-resolving arrays separated about 10 km apart. Tonal (CW) low-power (a few tens of Watts) source of the acoustic signal is towed around the area of interest with 3-5 kn speed. The phase difference of the acoustic signal at the interferometer related to a given acoustic mode induced by typical ocean mesoscale inhomogeneities is estimated of the order of unit. The errors of HRA due to inaccurate positioning of the source with the help of conventional satellite navigation are significantly less then those due to inhomogeneities. The most important source of errors is scattering at internal waves, which induces errors in HRA less, however comparable to HRA-signal. This error can be reduced by time-space averaging. In the numerical simulations performed it was assumed that IW induced HRA errors measured from two point separated by a few km becomes uncorrelated after 10-15 min time interval.

The simplest way to solve the inverse problem - inferring 3-D sound speed field basing on HRA data- is to assume in the first approximation that acoustic propagation is adiabatic. In this case inversion proceeds in two stage. At the first stage the values of propagation constants of different acoustic modes at the nodes of a horizontal grid are calculated. Owing to adiabaticity assumption each mode is processed independently. At the second stage the coefficients of the expansion of the variation of sound speed profile with respect to some set of empirical orthogonal functions are calculated basing on already determined values of propagation constants. This time different nodes of the horizontal grid are considered independently. As horizontal rays associated with different modes represent straight lines with high accuracy, the first stage represents completely linear procedure. The second stage is usually significantly nonlinear, however it is 1-D task which can be easily treated numerically.

The adiabaticity assumption may be not very realistic in some instances, and in this case an iterative approach is suggested. In this case each new iteration introduces some corrections into HRA data which take into account mode interactions and make propagation "more adiabatic". It was demonstrated, that in practical situations a few iterations is sufficient.

The results of numerical simulations will be presented and discussed.

Future Field Work

1630

Arctic Climate Observations using Underwater Sound (ACOUS)

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The Arctic Climate Observations using Underwater Sound (ACOUS, from the Greek, akous, meaning "listen!") program will be receiving travel time data continuously (once every 4 hours for the first 1-2 months and then once every 4 days for the next 1-2 years, before the source would need to be rebatteried) from a receive array in the Lincoln Sea and a receive array off Pt. Barrow, Alaska. These two receive arrays are cabled to shore. The source with a frequency of 20 Hz will be installed off Franz Josef Land, either in the Franz Victoria trough or the Santa Anna trough. The installations are planned for 1998. It is also planned to coordinate the ONR/NSF SCICEX program with ACOUS. The SCICEX program provides a nuclear submarine for a dedicated 40-60 scientific cruise in the Arctic. There have been three cruises so far in 1993, 1995, and 1996. Three more are planned for 1997, 1998, and 1999. Simultaneous CTD sampling and ice draft measurements along the acoustic propagation path are being proposed.

Travel times from the Transarctic Acoustic Propagation (TAP) experiment conducted in the Arctic in April 1994 showed faster arrivals for mode 2 as compared to U.S. and Russian historical climatology [Mikhalevsky, et. al., 1995]. This result indicated an average warming of approximately .4 degrees C along the propagation path from Svalbard to the ONR Sea Ice Mechanics Initiative (SIMI) ice camp that was in the Beaufort Sea at 2600 km range. These results were later confirmed by direct measurements from ice-breakers and the SCICEX submarine cruises [Mikhalevsky, et al., 1996]. The TAP experiment revealed the unique coupling of the acoustics and oceanography in the Arctic Ocean, demonstrating the value of acoustic thermometry as an important observational method for the Arctic.

The project has involved working closely with the Russians since 1991 and was begun as the Arctic Sub-Group of the ATOC program. Since December 1994, the project has been under the auspices of the Gore-Chernomyrdin Commission, and a bilateral agreement still in force signed by the then Secretary of Defense Bill Perry, and the Russian Deputy Minister of Defense Andrei Kokoshin.

The outyear plans for ACOUS include adding another source on the Lomonosov Ridge, and four additional autonomous receive arrays. The acoustic travel time data from ACOUS will provide year-round information about changes along the first two propagation paths. With the addition of the second source and the four receivers there will be data from the additional 10 paths, providing separate eastern and western Arctic basin coverage, and higher spatial resolution. It is hoped that ACOUS will lay the groundwork for a much expanded and more permanent acoustic monitoring network in the Arctic.

Mikhalevsky, P.N., A. Gavrilov, A. B. Baggeroer, and M. Slavinsky, "Experiment Tests Use of Acoustics to Monitor Temperature and Ice in the Arctic Ocean," Eos, Trans. Am. Geo. Union, Vol. 76, No. 27, July 1995.

Mikhalevsky, P.N., R. E. Keenan, and A. B. Baggeroer, "Measured transarctic travel times and model comparisons," Proceedings 3rd European Conference on Acoustics, Vol. 2, pp. 773-777, June, 1996.

1650

New directions in understanding acoustic propagation and tomography at basin-scales

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Innovations in understanding acoustic propagation and tomographic systems will be discussed. Topics include the modeling of sound over basin-scales and the relative ease with which tomographic systems may be implemented.

1710

North Pacific Acoustic Laboratory

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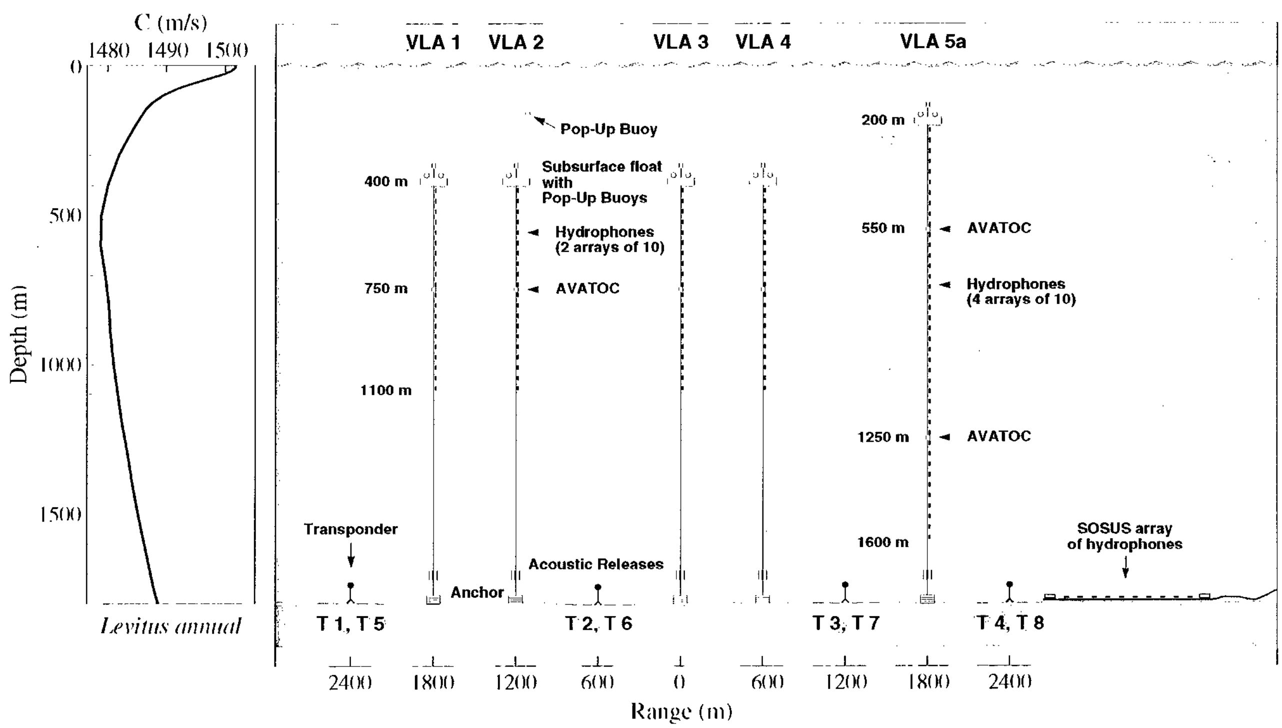
The ultimate limits of long-range sonar are imposed by ocean variability and the ambient sound field. Scattering from internal waves limits the temporal and spatial coherence of the received signal. Recent long-range transmissions as part of the Acoustic Thermometry of Ocean Climate (ATOC) project have demonstrated a remarkable degree of vertical coherence, permitting phase-coherent beamforming at megameter ranges. Ultimately, however, coherent wavefronts are destroyed by becoming increasingly convoluted and eventually breaking up into multiple sheets, creating a complicated sound field which negates the opportunity for phase-coherent analysis. There have been virtually no detailed observations of when and how this occurs.

The North Pacific Acoustic Laboratory (NPAL) project will take advantage of the acoustic network installed in the North Pacific by ATOC and the instrumentation developed for ATOC to improve our understanding of the temporal, vertical, and horizontal coherence of long-range, low-frequency resolved rays and modes. The North Pacific network consists of a broadband, 75-Hz acoustic source that was deployed off California in late 1995, a second source that will be deployed north of Kauai during summer 1997, and fifteen horizontal SOSUS arrays that have been instrumented for receiving and processing the signals from the two sources. In addition, the network includes large-aperture vertical receiving arrays developed for ATOC that were successfully deployed for nearly a year off Hawaii at 3300 km range and near Kiritimati (Christmas) Island at 5100 km range.

For the NPAL project, the vertical arrays developed for ATOC will be reconfigured as five vertical 700-m-long arrays spanning a total horizontal aperture of 2800 m to augment the existing (decommissioned) Sur Ridge SOSUS array. With this billboard array, the decorrelation of the signal transmitted by the Kauai source will be recorded.

Low-frequency noise is dominated by shipping and, ultimately, by wave-breaking processes. The resulting "granularity" of the noise field can be exploited for detection and localization purposes. Preliminary measurements of the noise field will be also be recorded by the sparse billboard array. Our ultimate objective is to understand the fundamental limits to signal processing imposed by these ocean processes.



Vertical Line Array (VLA) receivers deployed off Pt. Sur, California, during July, 1998 for the North Pacific Acoustic Laboratory (NPAL) experiment. The VLAs were deployed transverse to the acoustic path from the ATOC source installed north of Kauai.

Matthew Norenberg, John Kemp, and Kevin Hardy recovering a pop-up data buoy from the R/V *Melville* during the NPAL deployment cruise in July, 1998.